ELECTRONICS IN INDUSTRY

BY

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ELECTRONICS IN INDUSTRY

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To

Jo, George and Bob

PREFACE

To give a broad introduction to the use of electronic circuits and equipment is the purpose of this book. Intended mainly for men in industry, the book outlines the industrial uses of tube circuits and gives detailed explanation of a large number of electronic equipments now serving in industrial plants.

The subject is presented for the users of equipment already designed and built by leading manufacturers; it is of little interest or value to the designer or builder of electronic equipment. No previous knowledge of tubes is assumed; tubes are introduced gradually in simple operating circuits, to acquaint the reader with the purpose of electronic equipment before briefly exploring the nature of the tubes themselves. Beyond simple arithmetic in example problems, there is no use of mathematics.

The material is not arranged in the orderly classification found in most textbooks but aims to maintain interest. The text is based on an evening study course in industrial electronics taught in Detroit by the author for several years, and sponsored by the University of Michigan Extension Service. Here the students come from many industrial plants, desiring to gain a general knowledge of electronics so as to understand and service the equipment already installed. Some of these students have graduated from colleges before radio and electronics were taught; the majority have had little technical training. Although desiring to learn of tube circuits, they are quickly bored with tube details or classified fundamentals. For such men this book is written; it may serve as a text for use by similar groups.

There is no attempt to picture the application of electronic equipment or to discuss the results obtained. Occasional statements are not technically precise; to correct them would only confuse the average reader.

This book will supplement rather than duplicate the material found in other texts; by explaining many kinds of complete circuits, it aims to awaken interest in various phases of industrial

electronics so that the reader is encouraged to use other texts to obtain more complete coverage of desired subjects.

The author wishes to acknowledge the assistance of the Electronic Control Sections of the General Electric Company, especially that of A. E. Bailey, Jr., W. D. Cockrell, H. L. Palmer and their coworkers. Photographs have been supplied by General Electric.

GEORGE M. CHUTE.

DETROIT, MICH.,
March, 1946

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CHAPTER 1

CHOOSING ELECTRONICS FOR YOUR NEEDS

You know how electricity washes clothes, cooks your food, freezes your food, lights your home and runs streetcars and elevators; yet no single electrical device does all these things. In the same way, electronics is not just one tube or magic bottle; electronics is a complete system or part of electrical engineering. Electronics is the science or practice of using electricity in devices similar to radio tubes, so as to get results not possible with ordinary electrical equipment.

1-1. The Age of Electronics.—Although electronics has received greater attention during the war years, electronic equipment has been used for a quarter of a century. Without electronics you might have no radio, sound pictures, fluorescent lighting, public-address systems or long-distance telephone calls. Recall that most of these familiar equipments serve to carry or give information—communication has been the major purpose of electronics and still holds the interest of most workers and students in this field.

Meanwhile industry, seeking faster and more accurate methods of production, has adapted electronic equipment to its own needs. Gradually during the past 15 years industrial plants have installed tube-operated equipment to give better operation of motors, better spot or seam welding, and more useful heating of metal, along with the better known "electric-eye" control of varied operations.

Five years of mechanized warfare placed huge quantities of electronic devices in ships, planes and tanks; all this war material has come from industrial plants that use similar tube-operated equipments in manufacturing processes. These industrial equipments will remain in use after the end of war needs; electronics in industry is here to stay.

1-2. Electronics in Industry.—A list of ways whereby electricity is used in industry would fill many volumes. Similarly, there are thousands of tube-operated or electronic ways of getting

results; many books have described these industrial methods. For the reader who wants only a result and a clue to a method used, the references in this chapter are of direct interest.

Many kinds of electronic equipment are available to industrial users and are carefully designed for the severe requirements of life in a modern factory. These standard equipments are installed in such numbers that they are already familiar to the electrical personnel of many manufacturing plants. To show how these electronic equipments work, to give an understanding of industrial tube-operated circuits already in use, the following chapters are devoted.

1-3. All of Electronics Is Electrical.—No matter what result is desired or what kinds of tube or electronic device are used, this equipment is electrical. Understanding electronics includes the understanding of ordinary electric devices and circuits, some of which are reviewed herein.

Some people believe that electronic devices can hear, see, feel, smell or even think; this is true only when the sound, image, feeling or thought can be changed into an electric signal, to which the tube-operated device can then respond. Much of the success of electronics depends on the cleverness of the methods used to obtain an electric signal that can be used to stimulate the electronic device into action. This signal may be so small or so fleeting that it is ignored by ordinary electric devices; the tube-operated circuit can be made to detect such a signal, increase its strength and put it to useful work. We hear of no electronic device that will remove the roast chicken from the oven when its smell indicates that cooking is complete; when some device is perfected that will convert that certain odor into a corresponding electric signal, then our present electronic devices can do the rest.

1-4. References to Industrial Electronic Applications. To learn what new electronic devices are used or what problems of industry are solved by electronics, one must refer to numerous articles in various magazines. Several excellent lists of such articles have been published:

A Decade of Progress in the Use of Electronic Tubes in Other than the Field of Communications, *Electrical Engineering* (Transactions section), December, 1940, p. 650.

W. C. White's Where to Find Special Information on Electronic Uses in Industry, appears in *Electronic Industries* for June, 1943,

at p. 72; for February, 1944, at p. 96; also for February, 1945, at p. 102.

Similarly, a list of books published in various branches of electronics, Electronics Bibliography for War Training, appears in *Electronics* for May, 1943, at p. 109; for June, 1943, at p. 128.

In the study of the industrial branch of electronics, particularly for those circuit and tube details needed in the preparation of this book, the author finds the following very helpful:

HENNEY, K., "Electron Tubes in Industry," McGraw-Hill Book Company, Inc., 1937.

FINK, G. D., "Engineering Electronics," McGraw-Hill Book Company, Inc., 1938.

ALBERT, A. L., "Fundamentals of Electronics and Vacuum Tubes," The Macmillan Company, 1938.

EASTMAN, A. V., "Fundamentals of Vacuum Tubes," McGraw-Hill Book Company, Inc., 1941.

GULLIKSEN, F. H., and E. H. VEDDER, "Industrial Electronics," John Wiley & Sons, Inc., 1935.

COCKRELL, W. D., "Industrial Electronic Control," McGraw-Hill Book Company, Inc., 1944.

CAVERLY, D. P., "A Primer of Electronics," McGraw-Hill Book Company, Inc., 1943.

BATCHER, R. R., and W. MOULIC, "The Electronic Engineering Handbook," Electronic Development Associates, The Blakiston Company, 1944.

1-5. Too Many Vacuum Tubes?—Ordinary electrical equipment enters the electronic class whenever its circuit includes an electronic or vacuum tube. The special behavior of electricity within such a tube changes the performance of the entire circuit. Naturally we are first interested in the tubes themselves.

A newcomer to electronics is awed by the numerous tube types, styles, shapes and ratings. Although many of these are mentioned later, here let us divide all tubes into only two classes. The first class of tube has had all air pumped from inside it, and has then been sealed so that there is internal high vacuum; into the second class of tube, after it has been similarly pumped free of air, an amount of a certain gas or vapor is inserted before the tube is sealed. Both of these are known as vacuum tubes; but

they are correctly divided into high-vacuum types and vapor-filled types.*

1-6. High-vacuum vs. Vapor-filled Tubes.—Later chapters will show why all high-vacuum tubes have speedy and complete control of their circuits, unmatched by any vapor-filled tube; the vapor-filled tube can handle much greater amounts of current, but cannot decrease or interrupt this current flow. We may think of the high-vacuum tube as being of the "white collar" or professional class; it is able to respond to very small signals and will follow, although these signals may change a million times per second. It is ideal for most circuit operations, but usually lacks the brawn or ability to pass reasonably large amounts of current (such as one ampere). In comparison, the vapor-filled tube is of the laboring class; it has great current-carrying ability, it responds to a starting signal, but it cannot stop its own current flow or be used where signals change thousands of times per second. Both classes of tube will rectify (pass current in only one direction), just as both classes of worker must eat.

Until recent years the high-vacuum tube was found mainly in communication equipment, where the vapor-filled tube was almost unknown. It is natural that earlier electronic textbooks stress the high-vacuum tube and its use in radio and similar circuits; at that time vapor-filled tubes were used mainly as power rectifiers, seeming to warrant little textbook space. Today we find vapor-filled tubes included in certain communication equipments; the modern industrial electronic equipment, controlling high-current circuits to large motors, welders or furnaces by vapor-filled tubes, is supervised by groups of high-vacuum tubes.

While many tubes have been designed for special purposes, there are very few basic types of vacuum tube, when judged by their method of operation. In the next six chapters you meet only two or three tube types, but these may be used in an endless variety of circuits.

1-7. Tubes Close or Open Electric Circuits.—Vacuum tubes merely act as switches, which may close or open electric circuits at very high speed; or they may control the amount of electricity flowing through the space inside the tube. If someone could make a moving electric switch that would close and open its

* Sometimes high-vacuum tubes are called *hard* tubes, vapor-filled tubes are called *soft* tubes.

contact thousands or millions of times per second, or gradually change the amount of electricity in its circuit at such speeds, such a switch could equal the performance of some kinds of vacuum tube.

In this study of electronics in industry, perhaps one-fifth of our time is devoted to the vacuum tubes and to what takes place inside them. The study of the electric circuits outside the tubes will require more time; in these circuits we find resistors, capacitors, motors and reactors which may be well known to us in industrial power applications. When we introduce vacuum tubes into these circuits, the electrical changes are most rapid and interesting.

For simplicity, we will watch vacuum tubes operate in circuits having d-c power supply, before advancing to the corresponding a-c circuits which are more frequently found in industry.

CHAPTER 2

HOW ELECTRICITY PASSES THROUGH AN ELECTRON TUBE

We already know how electric current flows in motors, incandescent lamps, electric furnaces, transformers, and in magnetic control devices; the electricity always flows in the copper wire or other metal parts. But consider a stroke of lightning, where electricity jumps through space. The great electric pressure of lightning forces the electric current to pass through the air. In the same way, inside any radio tube, tiny electric currents are made to pass through the space separating certain parts in the tube. We say that such action—where electricity flows through space instead of being confined to metal conductors or circuits—is electronic.

2-1. Why Is It Called Electronic? —Years ago, scientists who were trying to explain how electricity passed through space, thought that such an electric current was a steady stream of tiny electrical particles. They called these particles *electrons*. Today, we believe that any electric current is made of countless numbers of electrons. Only when electricity passes through space, when the stream of electrons comes out of the metal into the open, is such action called *electronic*. Whenever electricity flows across the space inside a device that controls its stream of electrons, that device is called electronic.

2-2. Tubes Are Airtight.— In ordinary air, electrons seem bashful, and can be made to jump through space only by the pressure of high voltage. But if they are enclosed in a tube from which the air has been removed, the electrons flow across the space more easily. All electronic tubes are carefully sealed, to maintain the desired conditions inside the tube.

Some electric lights are electronic. The common incandescent light bulb is not considered electronic, even though it is enclosed like a radio tube, for the electricity flows entirely within the metal filament. In contrast, the fluorescent lamp is electronic,

for its light is produced by the action of electricity that flows through the space between the two ends of the lamp.

2-3. Tube Advantages. – Let us list five important ways in which electron tubes give operation unequaled by other electric equipment:

1. Electron tubes can respond to very small control signals, and produce a corresponding but larger signal. In this way, tubes increase, or amplify, the input signal.

2. Electron tubes can respond at speeds far beyond those reached by the most sensitive moving devices.

3. Acting at high speeds or high voltages, electron tubes can produce special radiations (such as radio or X rays).

4. Some kinds of electron tube respond to light, serving as electric eyes.

5. With alternating voltage applied, electron tubes can carry electricity in one direction, while refusing to carry it in the opposite direction. In this way, tubes change or rectify alternating current into direct current.

This last type of action exists in most electron tubes, whether or not we wish to use them as rectifiers. Let us watch the action of such a vacuum tube in an electric circuit.

2-4. Introducing the Rectifier Tube. In Fig. 2*A* we see an ordinary transformer winding *TR*, which can force current through a contactor coil *C*, whenever switch *S* is closed. We all know that the alternating current flows in both directions through the switch and through the contactor coil, and the curve beneath shows that both halves of the a-c voltage wave* are applied to the terminals of the coil. However, in Fig. 2*B* we substitute a vacuum tube *T* for switch *S*, to see what happens. In the complete symbol, Fig. 2*C*, we show that this simple tube has an anode, or plate, entering the top of the tube circle, while at the bottom there is a cathode. Having two elements (anode and cathode), this tube is called a *diode*.

The cathode is heated by the output of a small transformer winding and is usually red hot before electricity can flow through the tube. This electricity passes through the space between

* This wave picture, in Fig. 2.1, represents one complete cycle of a-c voltage, which changes from positive (above the line) to negative (below the line) and back to positive at the rate or frequency of, say, 60 cycles per second.

the cathode and the anode, even though there is no piece of metal connecting these two parts of the tube. So, in Fig. 2*B*, we must realize that the electric circuit may be complete, or closed, between cathode and anode of the tube, even though the circuit line is not shown as connecting these two points within the tube. To permit this electricity to flow through the tube, the cathode

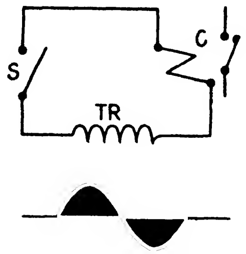


FIG. 2*A*.—The complete a-c wave passes through *S* to pick up *C*.

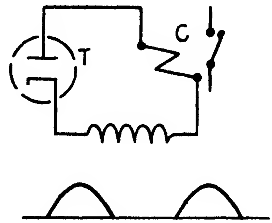


FIG. 2*B*.—Only half of the wave passes through tube *T*.

produces or emits electrons from its heated surface, which may be made of material such as tungsten. In simple diagrams such as Figs. 2*B* and 2*D*, we do not show the tube filament; we use a horizontal line within the circle, to represent the heated part of the tube which produces the electrons.

We find, with connections as in Fig. 2*B*, that current flows through the tube and the contactor coil, but the contactor

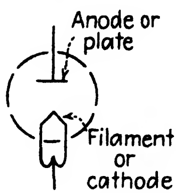


FIG. 2*C*.—Symbol of a diode tube.

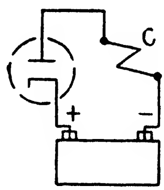


FIG. 2*D*.—No electrons flow while anode is more negative.

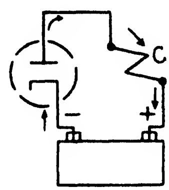


FIG. 2*E*.—Electrons flow when anode is positive.

chatters. Only a half wave of the a-c power supply is able to pass through the tube. Since we shall need to know which half wave can flow through the tube (or learn to distinguish whether the right-hand side of the transformer is positive or negative when current flows through the tube), we refer to Fig. 2*D*, where we have substituted a battery for the transformer and have connected the negative side of the battery to the contactor coil.

This means that the anode or top of the tube has a more negative potential than the cathode or bottom of the tube. With this connection we will see that the tube refuses to pass current. However, in Fig. 2*E* we have reversed the battery connection, so that the positive terminal is now connected to the contactor coil, and the anode has a more positive potential than the cathode. Current flows, energizing the contactor coil. This confirms our previous observation that current can flow in only one direction through an ordinary vacuum tube, and that these electrons flow only when the anode has a more positive potential than the cathode. The stream of electrons,[2-1*] produced at the heated cathode, flows through the tube from cathode to anode.

2-5. Why a Tube Works.—We have now learned three of the basic fundamentals of an ordinary vacuum tube: (1) heat is required at the cathode before this kind of tube can work; (2) current or electrons pass through space within the tube, requiring no metal conductor; (3) the electrons pass in one direction only, flowing from cathode to anode.

Let us study in detail why a tube works this way. If we merely had two wires connected to a source of voltage, and the ends of the two wires were slightly separated, in open air, we know that rather high voltage would be needed before this gap would break down and permit current to flow across the gap. Connected to an a-c supply, the current would jump across the gap in both directions. The current jumping such a gap may be quite large, in amperes. Actually, this current flow also consists of billions of electrons.

If we now enclose the ends of two wires as in a bottle, from which we then pump all the air, we find that rather high voltage is required to force even a small amount of current across the space between the ends of these wires. However, if we provide some way of heating the end of one of these wires, inside the enclosure, a small amount of current will easily flow across the space, with very low voltage applied. This was discovered over 50 years ago, when Edison was experimenting with his early electric-light bulb. In such a lamp, you recognize that he had an air-free enclosure, with a heated wire, the filament. One day,

* Small superior numbers used throughout this book refer to other sections where further pertinent information will be found. Here, for instance, it is suggested that the reader see Sec. 2-1 of Chap. 2.

to study an unusual action of the lamp, he inserted the end of another wire and found that he could measure a tiny flow of current through this second wire, connected outside to a battery, even though the wire did not touch any other object inside the lamp bulb. This observed "Edison effect" was a basic discovery upon which our entire subject of electronics depends.

2-6. The Electron Flow between Cathode and Anode.—In such a tube, the heated part, or element, is called the *cathode*. If electricity can flow through the tube when the cathode is hot, but refuses to flow when the cathode is cold, we realize that the heated cathode must be responsible for producing this current

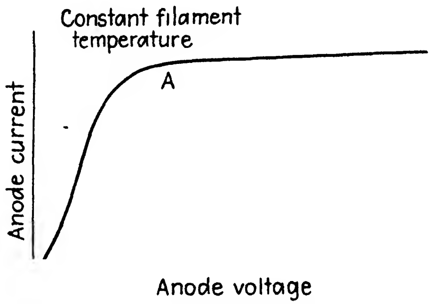


Fig. 2F How tube current increases with voltage

flow through the space. Today we have come to think of this current flow as merely a stream of electrons forced out of the cathode by the heat and attracted to the anode only when the anode is positive (as when it is connected to the positive battery terminal). To explain this, we say that electrons are negatively charged particles of electricity. Since such negative charges are attracted by an opposite, or positive, potential, the electrons rush toward the positive anode; when the anode becomes negative, the flow of electrons stops.

If we increase the anode voltage of a typical vacuum tube, the flow of electrons through the tube and its external circuit is also increased. This holds true up to the point where all the electrons produced at the cathode are being attracted to the anode, as at A in Fig. 2*F*. However, at higher anode voltages, we find that the electron flow (anode current) will increase further, if cathode temperature is raised to produce more electrons within the tube. We see that, as the temperature of the filament increases, more

electrons are forced to leave the cathode surface and enter the open space, where they can be attracted to the anode. However, a constant anode voltage attracts only a certain amount of electrons, producing anode current, shown at *B* in Fig. 2*G*. If the filament temperature is raised further, producing excess electrons, the anode current increases very little.

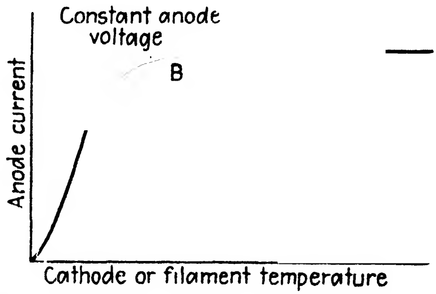


FIG. 2G How tube current increases with temperature

2-7. Do We See Electrons?—This question of causing electrons to be emitted or forced out of the cathode is of special interest here, mainly because it explains why the subject of electronics is so frequently illustrated by pictures of particles whirling in colored orbits, etc. Such pictures are merely the physicist's mental picture of how electrons behave while they gain sufficient energy (from added heat) to break loose finally from the bonds that hold them within the atom, and thereby jump into space. For our purpose, we need not concern ourselves further with this idea of whirling electrons and their orbits. All we need to know is that inside an electron tube large quantities of these electrons are driven into the open space, where they may be controlled more easily and more rapidly than when these same electrons are still flowing in an ordinary metal circuit.

If we operate a glass high-vacuum tube, properly connected in its socket, we can usually see the red-hot filament, but no other evidence of its operation. The amount of current through such vacuum tubes is usually a few milliamperes, or thousandths of an ampere. The other class of tube (vapor filled, see Sec. 9-1), which can carry more current, shows not only the red-hot filament but also a blue or purple glow when electrons are flowing through the space between cathode and anode.

2-8. Changing Alternating Current (A.C.) Into Direct Current (D.C.).—In electronic circuits, we often need some direct current, although the whole equipment may operate on a-c supply. One or two small tubes may be included for this purpose alone, acting as rectifiers. Similar to Fig. 2*B*, a single diode[2-4] may be used, which permits only one-half of each cycle of a.c. to reach the load, or d-c circuit; this pulsating output must be smoothed or filtered[10-4] before it becomes a useful d-c supply. This half-wave rectifier is most useful in communication circuits and electronic instruments, which require small amounts of d.c. at high voltage.

To produce a somewhat larger amount of direct current, two such diode tubes may be combined into one circuit, so as to

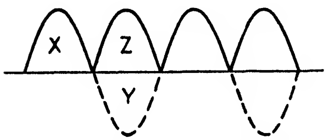


FIG. 2*H*.—Output waveshape of two-tube rectifier.

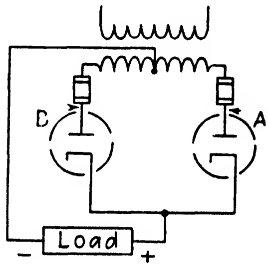


FIG. 2*I*.—Two-tube rectifier, passing both half waves.

rectify and use both halves of the a-c supply voltage wave. The output waveshape of such a two-tube rectifier is like the solid lines in Fig. 2*H*, and often must be smoothed into more useful form. The basic circuit of this rectifier appears in Fig. 2*I*. In Fig. 2*I*, a transformer is shown whose secondary winding is connected through fuses to the anodes of the two tubes. The cathodes of the two tubes are connected together and form the positive connection to the load. The negative load terminal connects to a mid-point of the secondary winding of the anode transformer. The a-c power supply causes point *A* to be more positive than *B* during one-half of each cycle. During this half cycle (shown as *X* in Fig. 2*H*), the voltage of the right half of the transformer secondary winding forces electrons to flow from the transformer center tap to the load, and through the right-hand tube to point *A*. At the same instant, point *B* is at a more negative potential than the transformer center tap, and it is impossible for current to flow through the left-hand tube. One-

half cycle later (as during *Y* in Fig. 2*H*), point *B* is more positive, and the left-hand half of the transformer forces electrons to flow from the transformer center tap through the load and left-hand tube to point *B*. Notice that the flow of electrons through the load is always in the same direction, regardless of which tube carries the current; therefore, during half-cycle *Y* of Fig. 2*H*, the voltage across the load is also above the horizontal line, as at Z.

2-9. Use of Oscilloscope.—To demonstrate the operation of this rectifier and show these wave-shape patterns (such as Figs. 2*B* and 2*H*), we use an oscillograph or oscilloscope. The cathode-ray oscillograph (see Sec. 27-5) is itself an electronic device. This "scope" contains a high-voltage electron tube, which is able to focus its stream of electrons so that they strike the end of the tube, causing a green spot where the electrons strike the fluorescent material at the end of the tube. When the scope (like a voltmeter) is connected across the load circuit of this rectifier, the green spot on the scope screen is made to trace a pattern or picture that shows the changes in voltage across the load during each cycle. With the scope adjusted so that it shows two complete cycles on the screen, we obtain the pattern shown in Fig. 2*H*. If we open the anode circuit of one of the tubes, we see that the scope picture resembles Fig. 2*B*, since with one tube disconnected, the other tube acts as a half-wave rectifier.

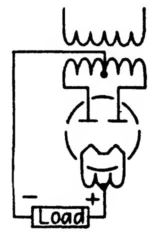


FIG. 2*J*.—Two anodes in a single rectifier tube.

2-10. Full-wave Rectification with One Tube. Where small amounts of direct current are needed, such as could be furnished by a pair of high-vacuum rectifier tubes, it is quite customary to combine the parts of two such diode tubes into one envelope or enclosure, forming a duplex tube. This is shown in Fig. 2*J*, using a small full-wave* rectifier tube, such as the well-known types 80 or 83. This circuit operates the same as the two-tube circuit of Sec. 2-8. Note that the cathodes are connected together inside the tube. The electron flow between the cathode and the left-hand anode has no effect on the corresponding stream of electrons between the cathode and the right-hand anode. There is no electron flow from one anode to the other anode; neither anode is heated or emits electrons to produce such a flow.

* This is more correctly called a biphase half-wave rectifier.

2-11. Types of Electron Emitter or Cathode.—In many tubes, the cathodes are merely the filaments; the electron stream comes directly from the surface of the hot filament,* as indicated in the tube in Fig. 2*J*.

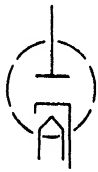


FIG. 2*K*.—Diode with indirectly heated cathode.

Other tubes, usually larger or industrial types, need cathodes that can produce much greater quantities of electrons; these tubes are built with indirectly heated cathodes, as is indicated in the tube symbol in Fig. 2*K*. In such a tube the heat is produced in a filament, which heats a separate cathode structure,† whose surface is better suited to emitting large quantities of electrons. Such a cathode may be like a metal sleeve surrounding the filament, but probably has no electrical connection to the filament. The cathode emits the electron stream; the filament merely keeps the cathode hot and therefore is frequently omitted in simplified diagrams, as in Figs. 2*D* and 2*I*. A tube consisting of an anode, a filament and an indirectly heated cathode is classed as a diode; it has two separate elements, not three.

* The metal filament may be coated with an oxide, thereby greatly increasing the electron emission or permitting operation of the filament at lower temperature.

† Tubes with indirectly heated cathodes require a longer warming period before their cathodes can reach the temperature required for satisfactory electron emission.

CHAPTER 3

CONTROL OF ELECTRON FLOW WITHIN A TUBE

The tubes previously described are diodes, or rectifiers, which act merely as valves and allow current to flow whenever positive voltage is applied to the anode.

3-1. Adding a Grid.—Here we will show how an electron tube of the high-vacuum type can be controlled by adding a third element, which is called the grid. With three elements—anode, cathode and grid—the tube is classed as a triode. Here we speak only of the high-vacuum type of triode, called the *pliotron*. The new fundamental to learn is that such a three-element tube acts as an amplifier—that is, a signal (a small change of potential at the grid) controls a considerable flow of current through the tube. A large amount of amplification (or increase of power) can be obtained by combining a number of tubes in such a way that each tube amplifies the output of the previous tube. This feature of amplification is basically important in the study of electronics, for it is the secret whereby a radio loud-speaker shouts in response to the small signal received from a transmitter hundreds of miles away, or it makes it possible for a 10-hp motor to move a gun turret to follow a signal reflected from an airplane miles above, in darkness.

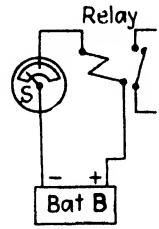


FIG. 3.1.—Meter contact *S* must carry relay-coil current.

3-2. A Contact Problem.—To demonstrate a simple need for using an electron tube, Fig. 3.1 first uses a contact *S* to close the circuit to a small relay, whose coil is then energized by battery *B*. Here *S* happens to be a tiny contact on the pointer of a voltmeter (which is moved by changes of voltage in some external circuit not shown); it may close or open the circuit many times, but *S* soon becomes pitted or damaged by the current needed to energize the relay coil, even though that current is only $\frac{1}{100}$ ampere. To solve this difficulty, the electron tube is introduced.

3-3. The Electronic Answer.—In Fig. 3*B*, we have kept the same contact-making voltmeter, and we have kept the same relay coil, but between these two devices we have now inserted a three-element vacuum tube or amplifier. To make this electron tube *T* work, we must, of course, provide means of heating the cathode and we must also provide a power supply to furnish the necessary potential at the anode of the tube, so as to force the electrons to flow through the tube and through the coil of the relay. For simplicity, we have shown these power supplies in the form of batteries. Looking back to the days of the battery-operated radio sets, you may recognize this A battery as the low-voltage source for heating the tube cathode, while the B battery furnishes perhaps several hundred volts for the anode circuit of the tube, and the C battery is for the required negative grid voltage. Notice that the B battery must be positive on the right side, which is connected to the tube anode.

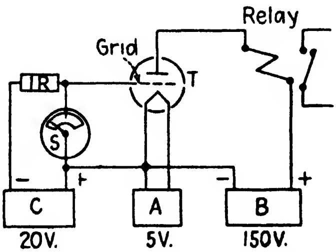


FIG. 3*B*.—Contact *S* controls tube *T*, to pick up the relay.

In the symbol for this tube shown in Fig. 3*B*, we have shown not only the anode and cathode, but we have added a third element, the grid. We have connected this grid to one contact of the contact-making voltmeter *S*. The other contact is shown connected to the cathode of the tube. When this voltmeter's contacts close, they connect the grid of the tube directly to the cathode of the tube, so that the grid is at the same potential as the cathode. In this condition, the tube passes current almost as though there were no grid at all. However, when the *S* contacts are open, you will see that the grid is not at cathode potential, but is at a negative potential, supplied by the C battery. With the instrument contacts open, there is no current flowing through the high resistance 1*R* (approximately 3 megohms), so there is no voltage drop across this resistor. When the grid of this tube is made as much as 15 or 20 volts more negative than the cathode of the tube, the tube electrons cannot flow from cathode to anode, even though the anode may be several hundred volts more positive than the cathode. As long as the *S* contacts remain open, this negative voltage at the grid will prevent

current flow and will thereby prevent the closing of the relay contacts.

However, just as soon as the voltmeter contacts close, the grid of the tube is connected directly to the cathode of the tube and no longer has a negative potential. It will no longer prevent the flow of electrons between the cathode and the anode of the tube, so the relay picks up and closes its contact. Notice that the amount of current flowing through the voltmeter contacts is now only a few millionths of an ampere. This current is so small that it will not damage the sensitive instrument contacts and is also too small directly to energize the coil of the relay. Yet by inserting the electron tube in the circuit and with very small current in the contacts, it is easily possible to change the potential at the grid of the tube so that the tube can thereby be made to allow the flow of an amount of current necessary to energize the relay coil. Naturally, we want to study the characteristics of this three-element tube to see how such a change of a few volts at the grid of the tube is able to control the current flowing through the tube and the relay coil.

3-4. Action of the Grid.—The tube in Fig. 3*B*, having three elements (anode, cathode and grid) is called a *triode*. To help explain the behavior of this tube, Fig. 3*C* shows how the anode current changes as the grid voltage changes. With zero grid potential, this certain tube allows a flow of 15 milliamperes. A change of only a few volts at the grid causes a large variation in the anode current. Since the anode of the tube is more positive than the cathode under normal operating conditions, it attracts the emitted electrons from the cathode. These electrons traveling to the anode become the anode current. To prevent the flow of electrons to the anode, the grid of the tube is given a more negative potential (bias) than the cathode; we say that the grid voltage is negative. This negative voltage repels the electrons in the direction opposite to the pulling force of the anode. When the repelling action of the grid and the pulling force of the anode become equal, or neutralize each other, the electrons are no longer urged to move to the anode, so the anode current becomes zero.

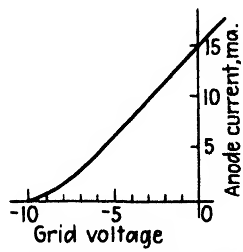


FIG. 3*C*.—How tube current is changed by grid voltage.

In Fig. 3C we see that the grid voltage must be lowered to minus (−) 10 volts to stop the anode current

The action of the grid is similar to that of a valve in a water pipe. A small amount of energy, applied to opening and closing the valve, controls a much larger amount of energy represented by the water flow under pressure.

3-5. Grid Current.—Whenever the grid is more negative than the cathode, no current flows in the grid circuit, since no electrons are attracted to the grid from the cathode. However, when the grid is made positive, there is current flowing in the grid circuit; under these conditions the grid and the cathode become the two elements of a rectifier and there is a rectified flow of electrons from cathode to grid Some electrons emitted by the cathode are attracted to a more positive grid in exactly the same way as these electrons are attracted across the greater space to a more positive anode.

3-6. Mechanical Arrangement of a Triode.—A sketch of the internal structure of a triode is shown in Fig 3D The cathode is

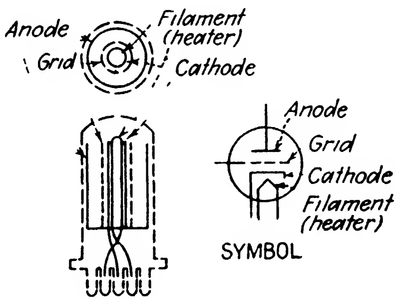


FIG. 3D —Structure and symbol of a triode tube.

located near the center of the tube. If the cathode is indirectly heated,[2-11] the filament is inside the cathode. Around the cathode is a grid, which is usually made of a fine wire or screen mesh. The grid and the cathode are surrounded by a metal cylinder, called the *anode.* Notice that the grid is located nearer to the cathode than to the anode; the distance between the grid and the cathode, compared to the distance between the grid and the anode, has an effect on how much the tube will amplify.

3-7. Gradual Control of a Tube.—In Fig 3B, we caused a large increase of tube current by closing the contact *S*. If we wish gradually to increase the current passing through tube *T*, we use

a variable resistance $2R$, or rheostat, in place of contact S, leaving the rest of the circuit unchanged, as shown in Fig. 3E. With $2R$ turned counterclockwise, so all its resistance is in circuit, half of the C-battery voltage* appears across $2R$, so the potential of grid G is about -10 volts (10 volts more negative than cathode K) and tube T passes no current. If we now turn $2R$ clockwise slowly, the potential at grid G gradually becomes less negative, or rises closer to the potential of cathode K; this permits more current flow through tube T, until this current becomes great enough to pick up the relay.

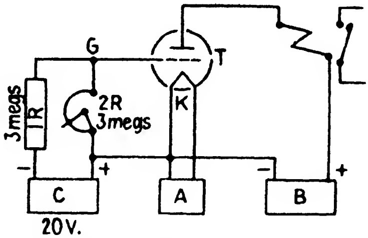


FIG. 3E.—Gradual control of tube T by $2R$.

3-8. The Phototube.—To obtain a photoelectric relay, we merely substitute a phototube P in place of $2R$, as shown in Fig. 3G. We recognize the phototube as the "electric eye." The type of phototube used in most photoelectric or light relays, is merely another form of diode—a two-element tube having a cathode and an anode, like any ordinary rectifier tube. It is shown in Fig. 3F. The phototube has no filament or heated cathode like the tubes already mentioned. Instead, its cathode is usually a half cylinder of metal whose inner surface, when receiving light, is able to emit electrons. The energy of light rays striking the surface of special alkali metals (such as potassium, or caesium oxide deposited on copper or silver) releases electrons from the metal, in the same way that the energy of heat in

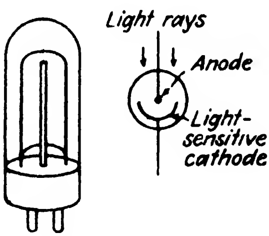


FIG. 3F.—Phototube and its symbol.

* These resistors $1R$ and $2R$ are in series and act as a voltage divider across the 20-volt C battery. The same current flows through $1R$ and $2R$, so the voltage across each resistor depends only on the amount of ohms of $1R$ and $2R$. When the entire 3-megohm resistance of $2R$ is in circuit, the voltage across $2R$ is equal to the voltage across $1R$, or 10 volts apiece. If we turn $2R$ until its circuit resistance is only 1 megohm, while $1R$ remains 3 megohms, one-fourth of the 20 volts appears across $2R$, three-fourths across $1R$. If $2R$ is turned entirely clockwise, $2R$ has zero resistance, and no voltage across it; the entire 20 volts then appears across $1R$.

other tubes releases electrons from the cathode. An increase in light reaching the inner surface of the phototube's cathode causes an increase in the flow of current or electrons through the tube. As in any diode, the phototube current flows only when the anode is more positive than the cathode (for the positive anode attracts the electrons, which are negative electrical particles).

3-9. A Light-sensitive Relay.—In the circuit of Fig. 3G, the wire anode of the phototube is connected to the positive terminal of battery C. The battery tries to force electrons through 1*R* and phototube *P*. However, as long as no light reaches the phototube cathode, the phototube acts like a very high resistance and passes almost no current. By gradually increasing the amount of light, we let the phototube pass more and more electrons, or decrease its amount of resistance. In this way, phototube *P* controls tube *T* (in the same way as 2*R* in Fig 3*E*); more light shining on the phototube causes grid *G* to become less negative, and this permits tube *T* to pass more current

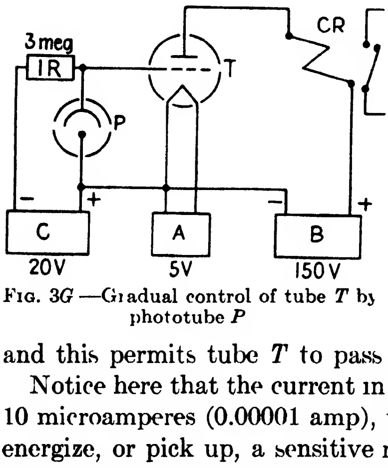


FIG. 3*G*—Gradual control of tube *T* by phototube *P*

Notice here that the current in the phototube is not more than 10 microamperes (0.00001 amp), which is far too small directly to energize, or pick up, a sensitive relay. However, by connecting the phototube in the grid circuit of amplifier tube *T*, this tiny current easily controls the amplifier, which in turn passes 0.01 amperes to energize relay *CR*. This explains why light-sensitive metals, although they were discovered 50 years ago, did not give us a photoelectric device operated by light until the amplifier tube had been perfected to act as the connecting link.

The response of the phototube to various colors or amounts of light will be described later.[19-11] For the present, let us realize that the phototube current increases in response to an increase in total light reaching the sensitive cathode surface. In this way, the phototube acts like a variable resistance,* whose ohms

* This applies to the usual photoemissive type of phototube, such as the PJ23 or GE923. Other types, known as *photocells*, such as those used in certain light meters, need not concern us here.

decrease as the light increases. If the light changes gradually, the phototube current changes gradually, thereby causing a gradual change in the anode current of amplifier tube T.

3-10. Amplification Factor.—The gradual change of anode current, caused by gradual change of grid voltage, is shown in Fig. 3C; there the anode voltage is constant, at, say, 150 volts. To show that a change of anode voltage likewise affects the amount of anode current, we must add more performance curves, as shown in Fig. 3H. For this three-element high-vacuum tube (pliotron), an increase in anode voltage causes an increase in anode current, even if the grid potential is held constant. For

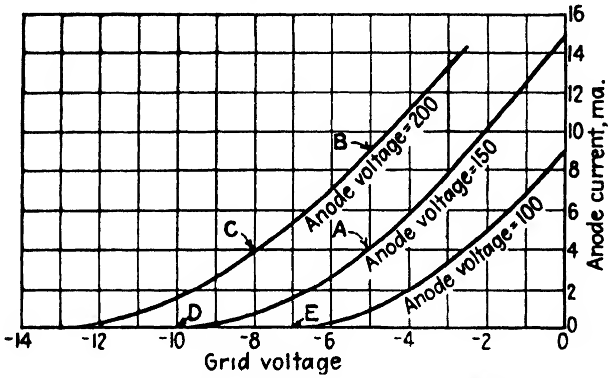


FIG. 3H.—Current of a triode is changed by anode voltage and by grid voltage.

example, Fig. 3H shows that if we hold the grid potential constant at -5 volts, the anode current is 4 milliamperes at 150 anode volts, (see point A), but rises to 9 milliamperes if the anode voltage is increased to 200 volts (point B). Notice that this current can be reduced to its original 4-milliamperes value by making the grid more negative, lowering its potential to -8 volts (point C). This demonstrates that a 50-volt rise in anode or plate voltage can be offset by a 4-volt decrease in grid potential. The ratio of these voltage changes, 50/4, gives us $12\frac{1}{2}$, which ratio is called the *amplification factor* for this certain tube. It shows that a 1-volt change at the grid is $12\frac{1}{2}$ times as effective in controlling anode current, as a 1-volt change at the anode. This ratio is commonly spoken of as the "mu" of the tube.

3-11. Cutoff.—The curves of Fig. 3H also show that, when the plate or anode voltage is 150 volts, the anode current is cut off or

becomes zero if the grid is 10 volts more negative than the cathode (see point D); minus 10 is called the *cutoff* value of grid voltage. When the grid is more negative than the cutoff value, no anode current can flow; above cutoff, anode current flows. Notice that this cutoff value changes; at 100 volts anode, cutoff is -7 volts (point E).

Questions

True or false? Explain why.

1. A phototube is a diode.

2. In most circuits the amount of anode current of a triode is controlled by changing the filament heat.

3. In Fig. 3B, the grid voltage is never positive.

4. In Fig. 3G, more light at phototube P changes the filament heat of tube T.

5. In Fig. 3G, some of the electrons passing through $1R$ may also pass through tube T.

6. Starting at point C in Fig. 3H, if the grid voltage is changed to -3 and the anode voltage is reduced to 150, the anode current is doubled.

CHAPTER 4

TIME-DELAY ACTION

Many common electric circuits in industry use time-delay devices, which operate a contact at some definite time after a signal is given; there are motor-operated timers and time delays produced while air escapes from a bellows. Industrial electronics includes great numbers of time delays; there are tube-operated time-delay relays; similar time-delay actions are used in most of the circuits shown later. Before studying such timing action in a tube circuit, let us see how an ordinary contactor may be kept energized for some time after the supply switch is opened.

4-1. Delayed Opening of a Contact.—When we close switch S in Fig. 4A, we pick up, or energize, contactor CR, so that it closes

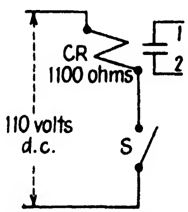


FIG. 4A.—CR drops out when S opens.

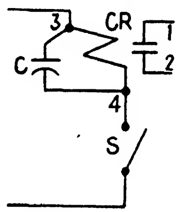


FIG. 4B.—Capacitor C delays the drop-out of CR.

its external contact between points 1 and 2. If the resistance of this contactor coil is 1100 ohms, the 110 volts across the coil causes a current flow of 0.1 ampere. Suppose that this contactor drops out when its coil current is decreased to 0.04 ampere. When we open switch S in Fig. 4A, the contactor CR drops out very quickly and opens its contact. How can we keep this contact closed for a few seconds after switch S opens?

This same contactor CR is shown again in Fig. 4B, but we have added a large capacitor or static condenser C. This capacitor is made of thin layers of metal foil separated by paper, as shown in Fig. 4C, so that the capacitor can store or hold electricity. When switch S closes, CR closes its contact; however, the 110 volts

across the coil now also charges capacitor *C*. When switch *S* is opened, capacitor *C* is still connected across *CR* coil; the electricity stored in capacitor *C* forces enough current (0.1 down to 0.04 ampere) to flow through the *CR* coil so that its contact does not open immediately. If capacitor *C* is very large, say, 1000 to 2000 microfarads, it stores enough electricity to hold *CR*

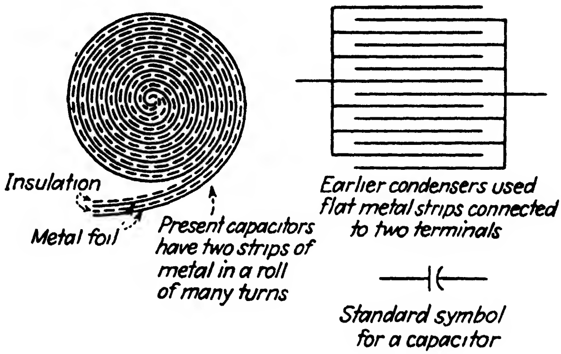


FIG. 4*C*.—How a capacitor is made.

closed for several seconds after *S* is opened. As will be shown later, the length of this time delay depends on the size of capacitor *C*, and depends on the ohms resistance of the contactor coil. Let us now use a similar capacitor-resistor time delay in a tube-operated circuit.

4-2. Opening a Contact to Energize a Tube Relay.—You will recall that in an earlier circuit, Fig. 3*B*, we closed contact *S* to make tube *T* pick up a relay. If we wish to reverse this action, so that we open *S* to cause tube *T* to pick up a relay *Z*, we merely interchange 1*R* and *S*, as shown in Fig. 4*D*. With *S* closed, the voltage of battery C appears across 1*R*, so the grid *G* is 20 volts more negative than cathode *K*; tube *T* passes no current. At the instant when *S* is opened, the C battery is disconnected from 1*R*; the voltage across 1*R* instantly disappears and grid *G* comes to the same potential as cathode *K*; tube *T* instantly passes current and picks up relay *Z*.

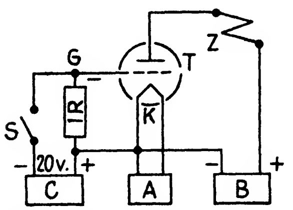


FIG. 4*D*.—Tube-*T* current starts as *S* opens.

4-3. A Time-delay Relay.—Suppose that we wish to pick up relay Z a short time after S is opened, or make the circuit operate as a time-delay relay. This is done merely by adding a capacitor $1C$ across resistor $1R$, as shown in Fig. 4*E*. Here, when S is closed, the C-battery voltage appears across $1R$ as before, and tube T passes no current. However, notice that $1C$ is also charged by this same 20 volts of battery C and stores some electric energy within itself. At the instant S is opened, the C-battery voltage is disconnected as before, but the voltage across $1R$ cannot instantly disappear, for capacitor $1C$ still holds some of its energy; for a short time, $1C$ acts like a tiny battery and forces current to flow through $1R$ (in the same direction as before), so that there still is a voltage across $1R$, which keeps the grid G negative. After several seconds delay, $1C$ will have lost enough of its charge so that the voltage across $1R$ becomes small enough to permit tube T to pass current and pick up relay Z. To produce this time delay, capacitor $1C$ may be less than 1 microfarad, for it discharges through the large 2-megohm resistance of $1R$; compare this with the 1000 mu f or 2000 mu f capacitor C required in Fig. 4*B*, where the coil resistance of CR is only 1100 ohms. In later circuits you will need to know how to estimate the length of time delay of such a resistor-capacitor (RC) combination.

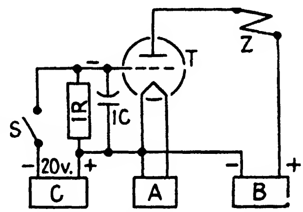


FIG. 4*E*.—Tube-*T* current increases slowly after *S* opens.

4-4. Speed of Capacitor Discharge.—When a capacitor is charged (either from d.c. or a.c.), it holds its voltage for some time. When the voltage supply to the capacitor is removed or shut off, the capacitor is left holding a definite amount of electricity, which it will try to get rid of through any path or circuit that it can find. If a big piece of metal is touched across the two capacitor terminals, the capacitor discharges instantly, usually causing a spark because of the sudden flow of discharge current through such a small amount of resistance. If a circuit of higher resistance (such as the 1100-ohm coil of Fig. 4*B*) is placed across the capacitor terminals, the capacitor will lose its voltage or charge more slowly, and the discharge current will be less. If a still higher resistance (like the 2-megohm resistor $1R$ in Fig. 4*D*) is connected across the terminals, the capacitor may discharge so

slowly that several seconds or minutes may pass by before the capacitor voltage is nearly gone. We see that a capacitor may be discharged quickly or slowly, but this depends upon the resistance of the circuit across the capacitor terminals.

4-5. The RC Time Constant. The rate of capacitor discharge may be fast at first, but it always becomes slower as the capacitor charge or voltage decreases. As shown in Fig. 4*F*, the capacitor voltage may decrease to about one-third of its full pressure in 5 seconds, yet 10 seconds later there is still some voltage left. If the size of the capacitor is known (in microfarads) and also the resistance (in megohms, which equal ohms/1,000,000), then the

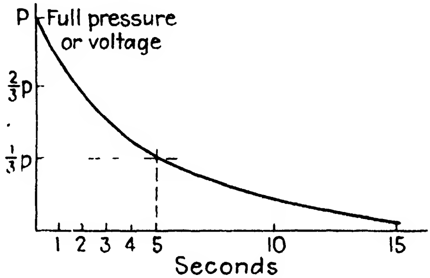


FIG. 4*F*.—Capacitor discharges rapidly at first, more slowly later.

length of time required for the capacitor voltage to decrease to approximately one-third of its starting value is shown by this relation:

Time (seconds) = resistor (megohms) × capacitor (microfarads).

For example, a 1-mu f* capacitor, discharging through 5,000,000 ohms (5 megohms) requires about 5 seconds to discharge to one-third of the voltage it had at the start. Similarly a 20-mu f capacitor with a 250,000-ohm resistor has this same rate of discharge.

This length of time, obtained by multiplying together *R* (resistance) and *C* (capacitance), we call the *RC* constant, or the *time constant*† of this resistor-capacitor combination. This time constant shows how long the capacitor voltage remains above

* Microfarad may be shown as mu f or mfd.

† This time constant, equal to *RC*, must not be confused with the length of actual time-delay of the circuit. Some circuits are designed to prevent a desired action until after a time delay equal to three times *RC* or even five times *RC*.

one-third its starting value. As shown in Fig. 4G, the remaining capacitor voltage is exactly 0.368 times* the original voltage, after the passage of time equal to RC; here the capacitor has lost 63.2 per cent of its charge. When time equal to $3RC$ has passed, the remaining voltage is 5 per cent, or 0.05 of its starting value.

Let us see how the information in Fig. 4G helps us understand a practical time-delay circuit.

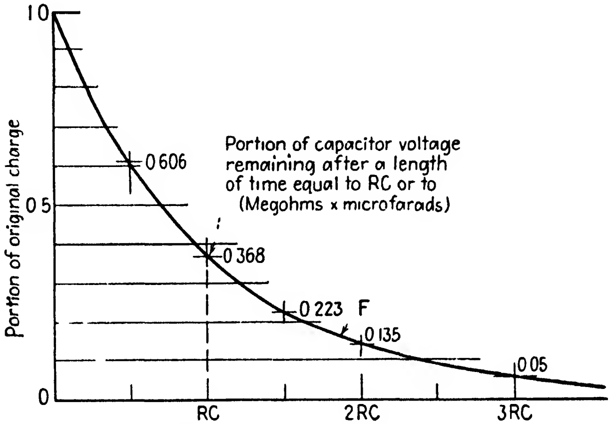


FIG. 4G Rate of capacitor discharge.

4-6. Time-delay Action in an Airplane.—Suppose that a pilot wishes to open an electric circuit and have it reclose automatically after a certain time delay. Figure 4H shows a circuit for this purpose, to operate from the 24-volt d-c power supply of the plane. When the pilot moves switch S from its upper position (as shown) to its lower position, the contact circuit between points 1 and 2 must open, then reclose after a number of seconds. From Fig. 4H, can we find this number of seconds' time delay? We can, if we are told that tube 1 passes enough current to pick up CR whenever the tube's grid is no more negative than -2 volts; we also assume that the tube's grid at point 7 is at the same potential as its cathode, whenever switch S is in the upper position.

With switch S in the upper position (as shown in Fig. 4H), electrons flow from cathode 5 to grid 7, through resistor $3R$ and

* This value 0.368 comes from the natural-rate-of-discharge curve. The study of electrical engineering tells us that this exponential curve is expressed by the formula $E_c = E_o(\epsilon^{-t/RC})$ volts. When time t is made equal to RC, then $E_c = E_o(\epsilon^{-1}) = E_o/2.718 = 0.368E_o$.

switch S, to the +24-volt potential at point 3. A voltage drop of 24 volts appears across resistor $3R$ and keeps capacitor $2C$ charged to this same voltage; the capacitor terminal at point 7 is 24 volts more negative than the 6 terminal. The tube grid 7 is

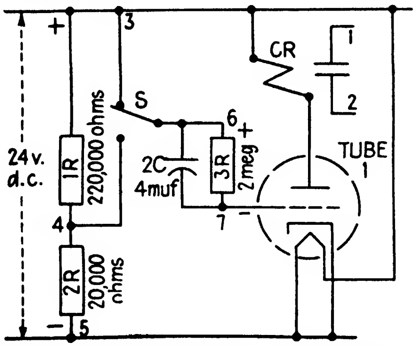


FIG. 4H.—Lowering S opens the CR contact, which recloses after a time delay.

at the same potential as cathode 5, so the tube passes anode current, which energizes relay CR, keeping contact 1-to-2 closed. These conditions are shown at the left side of Fig. 4I.

When S is moved to its lower position, this connects point 6 to a new potential at point 4, as shown at A in Fig. 4I. (From

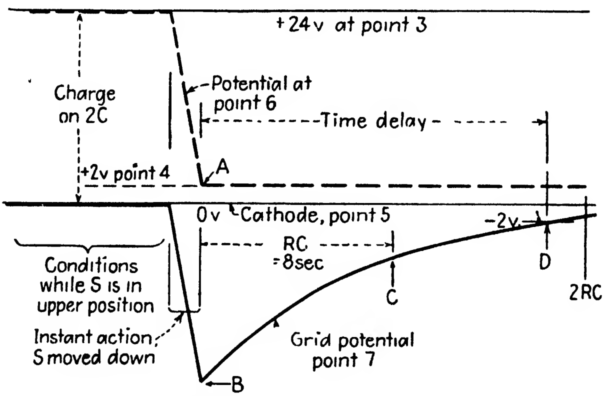


FIG. 4I.—Changes of potential in circuit of Fig. 4H.

the voltage divider $1R$ and $2R$, we see that point 4 is at +2 volts, or 2 volts more positive than cathode 5. Resistor $2R$ is 20,000 ohms; $2R$ and $1R$ total 240,000 ohms. Voltage drop across $2R$ = 20,000/240,000 × 24 volts = 2 volts.)

When the potential of point 6 is suddenly lowered by the movement of switch S, capacitor $2C$ holds its entire charge of 24 volts for a short time; the capacitor terminal 7 must still be 24 volts more negative than its terminal 6, so the grid potential at 7 is forced down to B in Fig. $4I$, which is 24 volts below point 4, or 22 volts below cathode 5. This negative grid voltage turns off the anode current of tube 1 and opens the 1-to-2 contact. At this same instant the time-delay action begins.

With switch S in the lower position, $2C$ is disconnected from the +24-volt supply, and begins to discharge through its own resistor $3R$. We calculate the time constant of $3R$ and $2C$ as 2 megohms $\times$ 4 mu f = 8 seconds. After this 8-second delay, the voltage across capacitor $2C$ is still 0.368×24 volts = 8.85 volts; as shown at C in Fig. $4I$, tube 1 has not yet picked up CR. The voltage across $2C$ must decrease further until it reaches point D, where the grid potential is -2 volts, with 4 volts across capacitor $2C$; here the anode current of tube 1 is large enough to pick up CR, reclosing the 1-to-2 contact. At this point D, capacitor $2C$ has discharged to 4 volts/24 volts = 0.167 times its starting value. Figure $4G$ now shows us (at point F) that this occurs after a time delay equal to $1.8RC$ or 1.8×8 sec. The time delay is 14.4 sec.

Questions

True or false? Explain why.

1. In Fig. $4E$, if $1R$ is 2 megohms and $1C$ is 3 microfarads, the time delay of the circuit is 6 seconds.
2. In Fig. $4E$, battery B may charge $1C$, by electrons flowing through tube T.
3. In Fig. $4E$, if $1R$ burns open, the time delay increases.
4. In Fig. $4G$, the shape of the curve changes if the capacitor has been charged to double voltage.
5. In Fig. $4H$, if $2C$ and $3R$ are changed to 0.5 mu f and 8 meg, the time delay becomes about 7 sec.

CHAPTER 5

TUBES IN A-C CIRCUITS

Pause a moment to realize that the circuits of Figs. 3*B*, 3*E*, 3*F*, 4*D* and 4*E* are exactly alike except for small changes in the grid circuit of tube *T*. Yet by these small changes we obtain first a "contact-amplifier," then a photo relay, and finally a time-delay relay. Of course, all these circuits operate from d-c power supplied by batteries. For commercial relays, we more often need to use a-c instead of d-c supply; when we convert any one of these circuits for a-c operation, we shall see that the same changes are necessary.

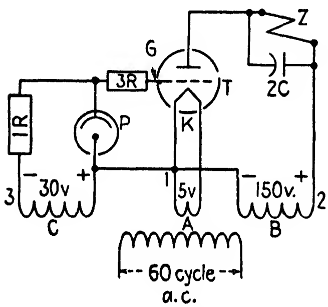


FIG. 5*A*.—Photoelectric relay with a-c power supply.

5-1. Substitution of A-c Power Supply.— If we substitute a-c supply to the photo relay of Fig. 3*G*, the result in Fig. 5*A* shows that we have merely used a transformer, whose three secondary windings *A*, *B* and *C* have replaced the three batteries. The 5 volts (rms[5-6]) of winding *A* heat the filament just as effectively as the 5-volt A battery. However, although winding *B* furnishes a complete a-c wave of voltage (so that point 2 is alternately more positive and more negative than point 1, as shown in Fig. 5*B*), winding *B* can force current through relay coil *Z* and tube *T* only during those half waves (such as *M*) when 2 is more positive than 1. During other half waves, such as *N* in Fig. 5*B*, the rectifying action of tube *T* prevents electron flow between its cathode and its anode.

5-2. Capacitor across Relay Coil.—This relay coil *Z*, in series with tube *T*, is energized by only half waves of the a-c supply; the relay may chatter unless some device is placed in the circuit to help, such as by adding 2*C* in Fig. 5*A*. Capacitor 2*C* charges to the voltage across relay coil *Z* while tube *T* is passing current, then 2*C* discharges during the next half cycle, maintaining partial

voltage across Z, as shown in Fig. 5B. Here you recognize the shape of the dotted line R-S as explained in Sec. 4-5; notice that the voltage across capacitor 2C decreases to about one-third in a half cycle of time;* it is recharged during the portion S-T of the next half wave.[5-6]

5-3. An A-c Photoelectric Relay.—This photo-relay circuit in Fig. 5A shows that, whenever a tube is used in an a-c circuit, we must check to see what happens during each half wave separately. So, in studying the grid circuit of tube T (whose voltage is supplied by transformer winding C in Fig. 5A), let us first watch that half wave when windings B and C have the polarity shown (which is also the half cycle marked M in Fig. 5B). If phototube P is dark and passes no current, no current flows through 1R, and grid G is at the same potential as point 3; since point 3 is much more negative than K (cathode), tube T passes no current, even though its anode is positive during this half cycle. However, if light shines on phototube P, electrons flow through P and 1R; the resistance of phototube P decreases, so that most of the voltage of winding C now appears across 1R. The grid G (forgetting 3R) is brought so near to the same potential as cathode K that tube T now passes current during this half cycle M, and picks up relay Z.

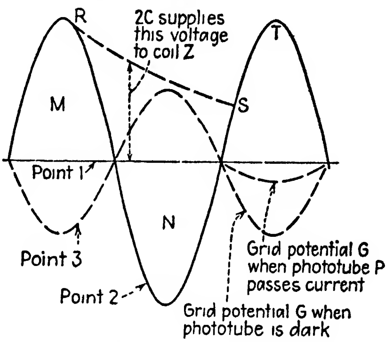


FIG. 5B. Voltage waveshapes in circuit of Fig. 5A.

5-4. The Use of Grid Current in A-c Circuits.—Is there any current flowing through 3R and the grid of tube T, in the circuit of Fig. 5A? During half cycle M (Fig. 5B) the grid G is always more negative than cathode K, so no electrons pass from cathode to grid or through 3R. However, during half cycle N the voltage of winding C forces a tiny electron flow from K, from cathode to grid of tube T, through 3R and 1R to point 3. (3R is a protective resistor to limit the amount of grid current to a safe value.) No

* From this we know that the time constant [4-5] of 2C, together with the resistance of coil Z, is about 1/120 or 0.008 seconds. If coil Z is 4000 ohms, capacitor 2C must be 2 mu f to produce this result.

electrons can pass upward through phototube P, for this tube also acts as a rectifier and prevents the passage of electrons, anode to cathode, even when illuminated. Notice that grid electrons can flow (from cathode to grid of tube T) during half cycle N, but cannot flow during half cycle M, for electrons never can flow from grid to cathode. Many a-c circuits make use of this feature, which is called *grid rectification.*

In the photo relay of Fig. 5A, a capacitor 1C is often used in place of 1R, and becomes charged by the flow of grid current during half cycle N. Its charge holds the grid G very negative during M; however, if light reaches phototube P, P passes enough electrons during M to discharge 1C and bring the potential of grid G close to K, letting tube T pick up relay Z.

We come to another circuit in which we must trace the action during each half cycle separately, before we see the combined result.

5-5. The Precipitron, or Air Cleaner.—Dust or smoke particles may be removed from air by the use of direct current at high

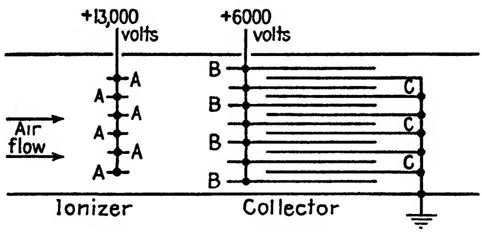


FIG. 5C.—Arrangement of a Precipitron air cleaner.

voltages. This high-voltage d.c. is connected to metal plates mounted in an air passage, as shown in Fig. 5C. As the air flows past the ionizer plates or wires A, any floating dust or solid matter becomes charged by the high-potential electric field around the 13,000-volt plates—each tiny particle of dust or smoke gathers a bit of this positive electricity. As the air then flows between the sets of plates in the collector, the dust particles (now positively charged) are repelled by the positive 6000-volt plates B but are attracted to the grounded plates C, which have the most negative potential in the system. The particles collect on plates C, from which the dirt is washed at intervals.

Similarly, articles placed at C may be coated with paint spray, sand or other fine particles blown into the air stream.

The required high-voltage potentials may be produced by tubes operating in a special rectifier circuit,* sometimes called a *voltage doubler*. As is shown in Fig. 5*D*, transformer *T* supplies a high a-c voltage, which is rectified by tubes *A* and *B* so as to charge capacitors 1*C* and 2*C*; across 2*C* is a voltage of 6 kilovolts (6 kv = 6000 volts), while 7 kv appears across 1*C*, so that the total voltage between points 4 and 6 is 13 kv. Let us trace the circuit during each half cycle separately.

Beginning with the half cycle (shown as *P* in Fig. 5*E*) when transformer *T* terminal 1 is most positive, electrons flow from terminal 3, through *R* to point 5, charge capacitor 1*C* and return through tube *A* to point 1. A half cycle later (during *N* in Fig. 5*E*), when terminal 1 is most negative, electrons flow from transformer tap 2, through tube *B* to grounded point 6, charge capacitor 2*C* and return through *R* to terminal 3. (*R* limits the current if the capacitors or plates should become short-circuited.) We see that the entire transformer winding 1-to-3 produces 7000 volts, across capacitor 1*C*; the portion 2-3 produces 6000 volts, across 2*C*. Capacitors 1*C* and 2*C* are large enough to furnish power to the ionizer and collector plates without losing much of their voltage between charges.

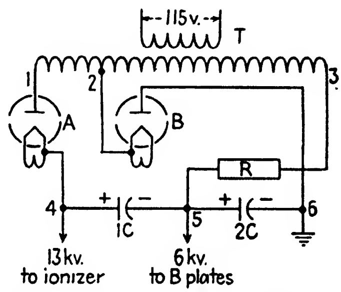


FIG. 5*D*.—Precipitron circuit, a voltage doubler.

5-6. Charging a Capacitor during a Half Cycle.—When a capacitor is connected to an a-c voltage, the voltage across the capacitor reverses during each cycle. When this capacitor is in series with an electron tube or any other rectifier, the capacitor is charged by current flowing in one direction only, during one half cycle. This is shown above, where capacitor 1*C* in Fig. 5*D* is charged by current through tube *A*. During the other half cycle, tube *A* passes no current, so the tube disconnects the capacitor from the a-c supply; capacitor 1*C* is left holding its charge of 7000 volts. Notice in Fig. 5*E* that this 7000-volt

* This complete combination of tubes, transformer and capacitors, designed to change low-voltage a.c. into high-voltage d.c., is called a *power pack*.

charge is produced by the maximum voltage during the tip, or crest, of the voltage wave. This voltage (7000 v. crest) corresponds to 4950 volts rms.* If we forget the voltage drop across

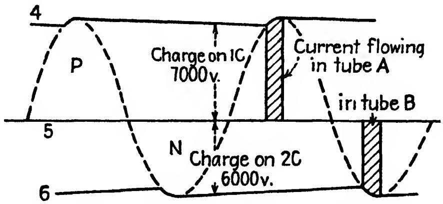


FIG. 5E.—Voltages in circuit of Fig. 5D.

the tubes and across *R* in Fig. 5*D*, then the transformer winding 1-to-3 must produce 4950 volts a.c. (as indicated by a voltmeter); for an instant during each half cycle, this voltage is as high as 7000 volts. Similarly, the portion of transformer winding 2-to-3 may produce only 4240 volts a.c., and yet be able to charge capacitor 2*C* to 6000 volts.

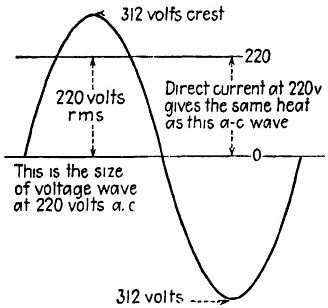


FIG. 5F.—Sine wave of a-c voltage.

In Fig. 5*E*, the shaded portions show the parts of the cycle when current flows in tube *A* or tube *B*, to recharge the capacitors to the crest voltage. During other parts of the cycle, the voltage supplied through a tube is less than the voltage of the capacitor; tube current will not flow. Only the rectifying action of the tubes prevents this high capacitor voltage from discharging into the lower voltage of the a-c line.

5-7. The Voltage Doubler.—While it is shown in a special form in Fig. 5*D*, the voltage-doubler circuit more frequently uses

* In an a-c circuit, the rapid changes of voltage or current are shown by a curve called a *sine wave.* Because of the shape of this a-c sine wave, shown in Fig. 5*F*, more than 220 volts is needed at the top of the wave in order to get the same effect as with a straight line of 220 volts d.c. A voltmeter shows 220 volts on its scale when it is connected to a circuit that has 312 volts (or $\sqrt{2} \times 220$ volts) at the top of the wave. Therefore, in a 220-volt a-c circuit, the voltage is as high as 312 volts for an instant during each half cycle. If 220 volts a.c. is connected across a capacitor, the capacitor can charge up to 312 volts. The 220 volts a.c. is called the *effective voltage*, or *rms voltage*, of the circuit, in which 312 volts is the *crest voltage.*

the same transformer voltage for each half cycle, in an arrangement shown in Fig. 5G. Here the a-c output of winding T forces current through tube A to charge capacitor $1C$ during one half cycle; during the following half cycle, the entire voltage of T is again used to charge $2C$, by forcing current through tube B. The

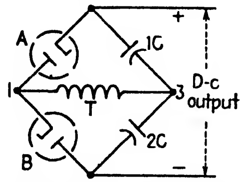


FIG. 5G.—Common voltage-doubler circuit.

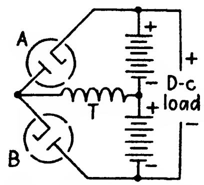


FIG. 5H.—Batteries used, to show action in Fig. 5G.

total d-c output voltage is twice as great as the crest value of the a-c voltage supplied by transformer T.

The action of this circuit is more easily seen if we substitute batteries in place of the capacitors, as in Fig. 5H. First, one battery is being charged and then the other battery is being charged; each battery receives current only half of the time, yet the two batteries provide a steady output current to the load, at double the voltage used to charge each battery separately.

5-8. An A-c Time-delay Relay.— Previously, in Fig. 4E, we watched a time-delay relay operating from batteries. To convert this d-c relay for operation from a.c., we replace the batteries with a transformer, as shown in Fig. 5I. Capacitor $2C$ is added as before, across coil Z; the connection to $1R$ and $1C$ is moved, and $2R$ is added. With switch S closed, during half cycle M (of Fig. 5B) the voltage of winding C forces electrons to flow only from point 3 through switch S and $2R$. During half cycle N, this flow is through $2R$ in the opposite direction; electrons also flow from K through tube T (cathode to grid) and through $1R$ and S to point 3. Most of the voltage of winding C, therefore, appears across $1R$ and charges $1C$ to this same voltage. During

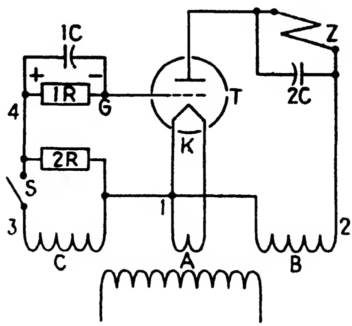


FIG. 5I.—A-c time-delay relay or contact amplifier (CR7511).

the next half cycle, when "grid rectification"[5-4] prevents current flow through 1*R* in the reverse direction, 1*C* loses a very small part of its charge by forcing electrons to flow through 1*R* (from *G* toward point 4). As long as *S* is closed, the voltage across 1*R* alone can keep grid *G* so negative that tube *T* passes no current.

In Fig. 5*I*, when *S* is opened, current through 2*R* stops instantly, and point 4 is at the same potential as cathode *K*. Voltage still remains across 1*R* while 1*C* gradually discharges through 1*R*; this voltage across 1*R* keeps grid *G* more negative than *K*. After the desired time delay (determined by the size of 1*R* and 1*C*), the voltage across 1*R* has become so small that grid *G* is near the same potential as cathode *K*, and tube *T* passes enough current to pick up relay *Z*. When *S* is reclosed, relay *Z* drops out instantly. (If a larger capacitor is substituted for 2*C*, its stored energy may be sufficient to keep relay *Z* energized for many cycles after tube *T* stops passing current[4-1].)

5-9. An A-c Contact Amplifier.—While the circuit of Fig. 5*I* gives time-delay operation, it is more often used as a contact amplifier—the a-c equivalent of Fig. 4*D*. If 1*R* and 1*C* are made small, the voltage across 1*R* disappears quickly; the opening of switch *S* causes almost instantaneous pickup of relay *Z*.

This circuit is used in an electronic relay available to industry. It operates on the amount of current that may flow through a wet thread or through any resistance less than 500,000 ohms. This electronic relay responds to a flow of current that is far too small to operate an ordinary magnetic relay.

Questions

True or false? Explain why.

1. A half cycle of 60-cycle a. c. is nearly the same as a direct current that flows for $\frac{1}{120}$ sec.

2. In Fig 5*A*, phototube *P* may pass current during those half cycles when the anode of tube *T* is negative.

3. In Fig. 5*D*, both capacitors are charged by electrons flowing through tube *B*.

4. When a 115-volt a-c motor is running, more than 150 volts is applied to it many times each second.

5. A capacitor charges to the same voltage if connected to either 115 volts d.c. or 115 volts a.c.

6. Suppose that transformer *T* produces 115 volts a.c. in Fig. 5*G*. Neglecting voltage drop across the tubes, the d-c output is close to (*a*) 115 volts, (*b*) 300 volts, (*c*) 230 volts, or (*d*) 150 volts.

CHAPTER 6

THE A-C TIME-DELAY RELAY

Several types of simple electronic time-delay circuit have already been described; let us study other a-c time-delay relays frequently used in industry.

6-1. A General-purpose Timer (General Electric* Type CR7504).—Figure 6*A* shows the circuit of a time-delay relay that is manufactured for general-purpose use in industry; it includes a dial 1*P*, which is turned for selecting the length of time delay. The circuit starts its time-delay action at the instant switch *S* is closed; at the end of the desired time delay, tube 1 picks up relay *CR*, whose contacts may be connected to close some other circuit or to open that circuit, if preferred.

In Fig. 6*A* the power supply is 115 volts, 60 cycles a.c., and the autotransformer (at left) increases this to 230 volts for use in the circuit of tube 1. A separate transformer winding *A* supplies the low voltage for heating the filament of tube 1. Notice here that tube 1 has a separate cathode (connected to point 4), which is indirectly heated; there is no electrical connection between the filament and the cathode; the red-hot filament heats the cathode so that the electrons flow through tube 1 from its heated cathode to the anode.

The electrons that pick up, or energize, relay *CR* must flow from point 5, through switch *S*, tube 1 and *CR* to point 6. Therefore, the closing of *S* makes it possible for tube 1 to pass current, but not until the grid of tube 1 reaches a potential that permits this current to flow; we shall see that the grid potential of tube 1 prevents the flow of this current until the end of the desired time delay. Reopening *S* drops out *CR* and resets the circuit for the next time-delay operation.

While *S* is open, the grid circuit of tube 1 is in action. During those half cycles when point 6 is more positive than point 5,

* In this book, all type numbers refer to units made by the General Electric Company, unless stated otherwise.

current can flow only through $1P$ and $3R$; no current flows through $1R$ or tube 1. However, during each half cycle when 5 is more positive than 6 (and S is still open), electrons flow from 6 through $2R$ to point 4, from cathode to grid of tube 1, through $1R$ to the slider of $1P$, to 5.

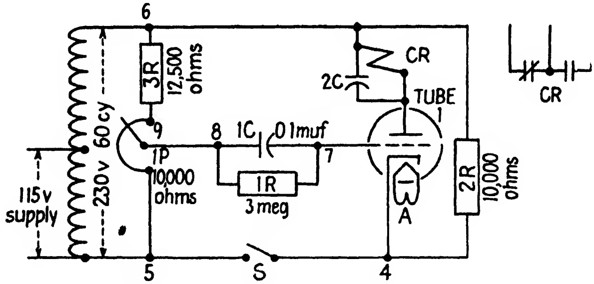


FIG. 6A — Circuit of time-delay relay (CR7504)

6-2. Circuit Action during a Long Time Delay.—First turn $1P$ so that its slider touches at point 5; the entire voltage between 5 and 6 (230 volts) now forces electrons through the $2R$-cathode-grid-$1R$ circuit. Since the 3-megohm resistance of $1R$ is so much greater than any other resistance in this circuit, as much as 200 volts appears across $1R$, and capacitor $1C$ becomes charged by

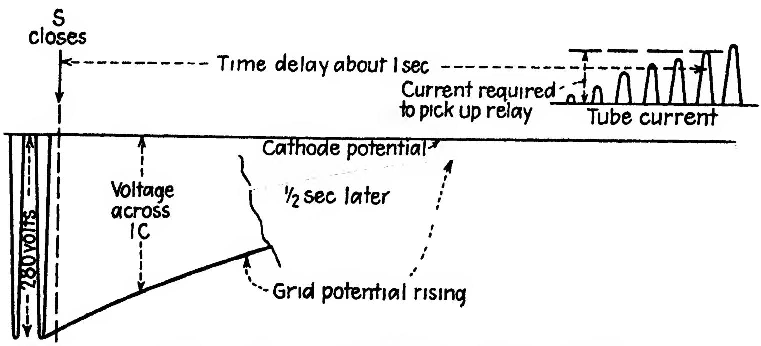


FIG. 6B.—Action in Fig. 6A, set for long time delay.

this voltage. Here 200 volts is the effective[5-6] (or rms) value of this a-c voltage wave, but capacitor $1C$ charges to the crest value ($\sqrt{2} \times 200$), or about 280 volts. During the next half cycle, the grid rectification[5-4] of tube 1 prevents any reverse flow of current; $1C$ loses only a very small part of its voltage by discharging through $1R$ (for the time constant[4-5] $1R \times 1C = 0.3$

second). So, as long as switch S remains open, about 280 volts is steadily maintained across $1R$, so that the point-7 end of $1R$ is 280 volts more negative than the point-8 end.

When switch S closes, connecting cathode 4 to point 5 and by-passing the cathode-grid circuit, capacitor $1C$ receives no further charge; $1C$ now continues to discharge through $1R$, so the grid potential becomes less negative, or rises as is shown in Fig. 6B. After about a 1-second delay (which is the longest time

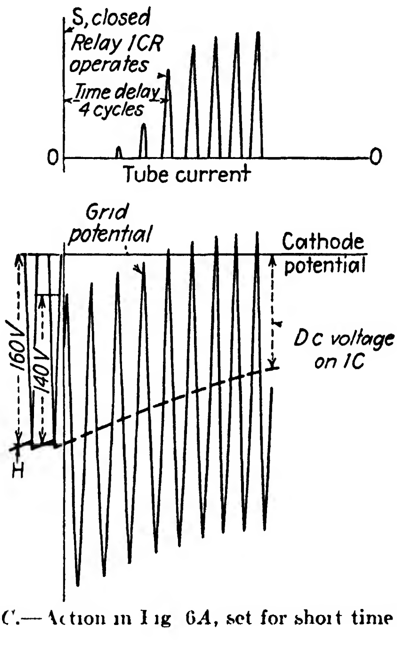


FIG. 6C.—Action in Fig. 6A, set for short time delay.

delay for which this certain relay may be set), the grid potential becomes so close to the cathode potential that tube 1 begins to pass current, which quickly increases to the amount required for the pickup of relay CR.

6-3. Circuit Action during Shorter Time Delay.—Now turn $1P$ so that its slider touches at point 9; only the voltage between 9 and 6 (about 130 volts) now forces electrons through the $2R$-cathode-grid-$1R$ circuit. About 115 volts is applied across $1R$, so that $1C$ charges to the crest value ($\sqrt{2} \times 115$), or about 160 volts, as shown at H in Fig. 6C. So point 7 is being kept 160 volts more negative than point 8.

When switch S closes, the grid of tube 1 is held negative by the charge of $1C$ as before; in addition, the a-c voltage across potentiometer $1P$ also influences the grid potential. Figure 6C shows how the grid voltage changes after S closes. Notice that the 140-volt crest of the a-c voltage across $1P$ is still less than the 160-volt charge on $1C$, so the grid of tube 1 is 20 volts negative. After a time delay of only four cycles, or 1/15 sec, the decrease of $1C$ voltage has raised the grid potential so close to the cathode that tube 1 passes current and picks up relay CR.

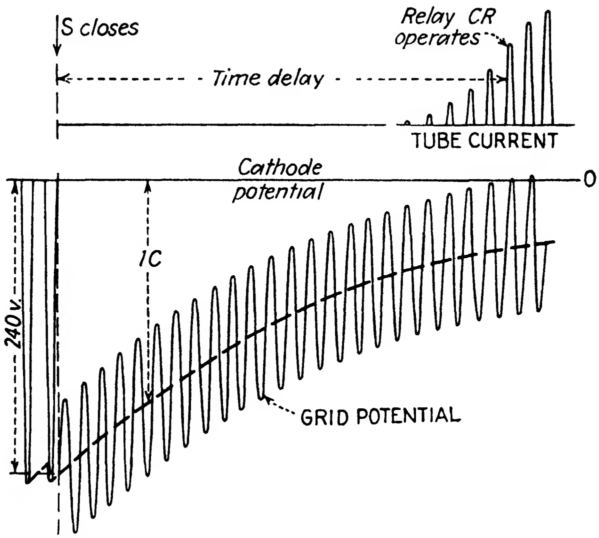


FIG. 6D.—Action in Fig. 6A, set for medium time delay.

Obviously, if $1P$ is set at a middle position, the resulting time delay will be about halfway between the longest value (Fig. 6B) and the shortest value (Fig. 6C). Figure 6D shows such a condition.

6-4. A Tube-circuit Problem.—At this point you may wish to see if you can solve a tube-operated circuit by yourself. Figure 6E is the elementary diagram of a weld timer, as given on the manufacturer's information sheet. The following questions may guide you. (*a*) Before closing the starting switch, is voltage present across either tube, anode to cathode? (*b*) If grid current can flow in tube 1, what does it do? (*c*) Is there any voltage that makes the tube-2 grid more positive or more negative than its

cathode? (*d*) When the starting switch closes, which tube instantly passes anode current? (*e*) Can anode current flow in tube 1 and also in tube 2 during the same half cycle? (*f*) How do 2*R* and 2*C* respond to the flow of anode current in tube 1? (*g*) How can 2*C* affect tube 2? The solution of Fig. 6*E* is given in Sec. 6-8.

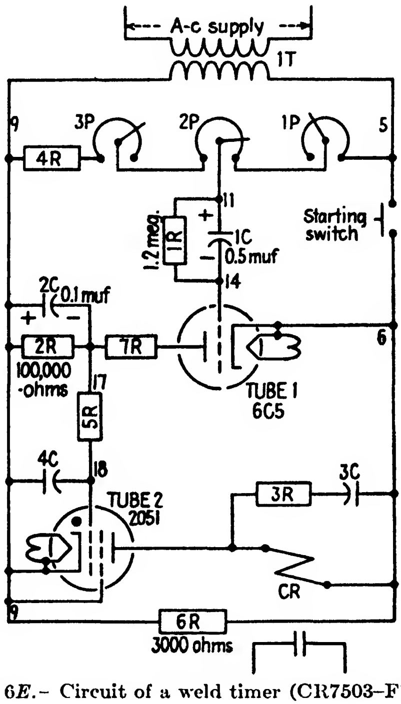


FIG. 6*E*.—Circuit of a weld timer (CR7503–F173).

6-5. Time-delay Circuit (Weltronic Model 53).—The circuit of Fig. 6*F* produces the same timing operation as the relay of Sec. 6-1. When you close the starting contact, relay *CR* closes its contact sometime later, after the desired time delay.

Figure 6*F* includes tube 2, three separate transformers, relay *CR* and a variable group of capacitors 3*C*. These capacitors, with their discharge resistor 3*R* and tap switch, are mounted together in one can. Notice that tube 2 is in a circuit, 2-to-3 and 7-to-9, which does not touch or connect to the power-supply circuit 5-to-6. The only way that electricity enters the tube circuit is through one of the transformers. Transformer 3*T*

furnishes the anode voltage necessary to force current through tube 2 and relay coil CR; in the grid circuit of tube 2, transformers $4T$ and $5T$ furnish 100 volts between points 7 and 8, and 100 volts between 8 and 9.

While the starting contact is open, $5T$ is the only transformer connected across the 115-volt supply; there is no voltage 1-to-3 in the anode circuit, and no voltage produced by $4T$ between 8 and 9. The 100-volt pressure from $5T$ forces a small flow of electrons through $3R$ into ground,* and from the other grounded connec-

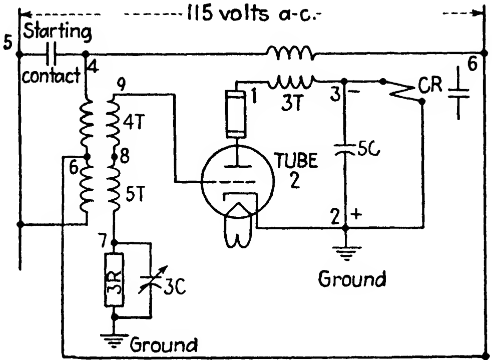


FIG. 6F.—Circuit of a Weltronic time-delay unit.

tion 2 through tube 2, cathode to grid, and through $4T$ to terminal 8 of $5T$. Almost all of this 100 volts a.c. appears across $3R$ and charges capacitor $3C$ to the crest of this voltage wave, or about 130 volts (see Sec. 5-6, footnote). During the next half cycle, grid rectification[5-4] prevents $5T$ from reversing the direction of electron flow in this grid circuit, so $3C$ keeps point 7 more negative than cathode 2.

When the starting contact is closed, transformer $3T$ produces anode voltage that tries to force current through tube 2. However, the 130-volt charge on $3C$ keeps the grid of tube 2 negative and prevents passage of anode current.

6-6. Voltages Out of Phase.—Closing the starting contact in Fig. 6F also energizes transformer $4T$, whose secondary winding now produces 100 volts. This 100 volts of $4T$ does not add to the 100 volts of $5T$, for the primary winding of $4T$ is connected out of

* Wherever two parts of a circuit are both shown connected to ground (symbol ⏚), these two parts are really connected together.

phase with $5T$, as shown in Fig. 6G. The 100-volt a-c wave of $4T$ exactly opposes or "bucks" the 100-volt wave of $5T$; a voltmeter still measures 100 volts across $4T$ alone or across $5T$ alone, but measures zero or no voltage across the two secondaries in series, or between points 7 and 9.

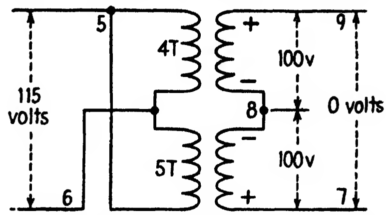


FIG. 6G.—Transformer voltages out of phase, or bucking.

Since the total voltage between 7 and 9 is now zero, capacitor $3C$ does not receive any fresh charge; instead, $3C$ starts to discharge through $3R$. When the charge on $3C$ decreases to a low enough value, the grid potential of tube 2 becomes close enough to the tube's cathode potential to let tube 2 pass current to pick up relay CR. The time delay of this circuit depends on the time needed for $3C$ to discharge through $3R$. To change the time delay, $3R$ remains unchanged but the size of $3C$ is changed in 10 steps; $3C$ consists of 10 small capacitors, with a dial switch to connect any number of them in circuit.

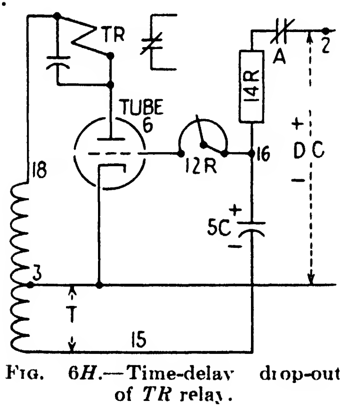


FIG. 6H.—Time-delay drop-out of TR relay.

6-7. Tube Current Shutoff after a Time Delay.—In most of the time-delay circuits we have studied, a tube is kept from passing anode current until after the desired time delay. In contrast, Fig. 6H shows a circuit in which, after contact A opens, tube 6 continues to pass anode current; after the desired time delay, tube 6 stops its current flow and relay TR drops out. This circuit appears as part of Fig. 23B, discussed later.

In Fig. 6H, the current through tube 6 and the coil of TR is supplied from the transformer winding (points 3 to 18). The grid of tube 6 is connected, through $12R$, $14R$ and contact A, to point 2. Since 2 is more positive than 3 (cathode), tube 6 is permitted to pass anode current. Also, there is a small flow of electrons from 3, through tube 6 (cathode to grid), through $12R$ and $14R$, to point 2. For a moment forget the T transformer

winding (or assume that points 15 and 3 are connected together); notice that capacitor $5C$ is now charged to the voltage between points 16 and 3, and the upper end of $5C$ is much more positive.

When contact A opens, this disconnects $14R$ from point 2. Although this action disconnects the tube-6 grid from the positive potential of point 2, there is no immediate effect on tube 6, for $5C$ still holds its charge, keeping point 16 more positive than 3. However, during the desired time-delay period, $5C$ gradually discharges by forcing electrons to flow through the cathode-to-grid circuit of tube 6 and through $12R$. As a result, the potential

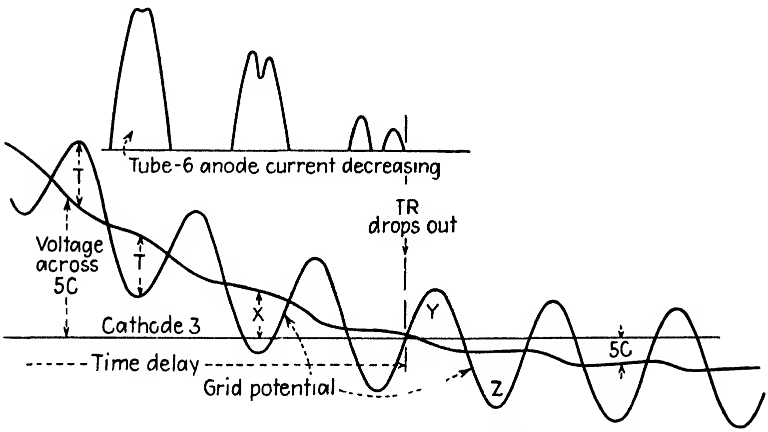


FIG. 6I. Tube current and grid potential in Fig. 6H.

of tube-6 grid becomes less positive and gradually decreases the flow of anode current in tube 6 and the coil of TR, approaching the point where TR finally drops out.

Even if $5C$ discharges completely, the grid of tube 6 reaches the same potential as the cathode 3 but cannot become more negative than 3 (as long as we forget the transformer winding T). We need to force the tube-6 grid still more negative so as to completely stop the anode current of tube 6 and drop out TR more definitely after the desired time delay. To do this, we include transformer winding T in series with capacitor $5C$; a small a-c wave appears in the tube-6 grid voltage, as is shown in Fig. 6I. After $5C$ has discharged to a small voltage, shown as X in Fig. 6I, the voltage of T forces $5C$ to discharge completely and to recharge in the opposite direction, as follows. During the half cycle Y, when point 15 is more positive than point 3,

this T voltage forces electrons to flow from point 3, through the cathode-grid circuit of tube 6, and through 12R into capacitor 5C, and back to point 15. This charges 5C so that point 16 becomes more negative than 3. During the following half cycle Z (when 15 is more negative than 3) electrons cannot flow in the reverse direction through the cathode-grid circuit, so 5C retains its charge and continues to hold point 16 (and tube-6 grid) much more negative than 3. Tube 6 now passes no anode current; TR drops out.

We can increase this time delay, before TR drops out, by turning 12R clockwise to increase its resistance. Since 5C must now discharge through this increased resistance, the discharge is slower, keeping tube-6 grid positive for a longer time.

6-8. Solution to Problem of Sec. 6-4.—Before the starting circuit is closed, no current can flow through either tube anode or through 2R or CR; therefore the CR contact is open. Meanwhile, in the grid circuit of tube 1, capacitor 1C has become charged by electrons flowing from point 9 through 6R, from cathode 6 to grid 14, through 1R, 2P and 1P to point 5; we see that this tube-1 circuit is a time-delay relay like Fig. 6A, and the voltage across 1C keeps grid 14 more negative than point 5. Also, since there is no current flowing through 2R, there is no voltage or charge on 2C, and grid 18 of tube 2 is at the same potential as its cathode 9. When the starting switch closes, tube 2 has no grid bias;* electrons flow instantly from 9 through tube 2 and CR to 6, and relay CR closes its contact. However, although full anode voltage now appears across tube 1, the charge on 1C holds the grid 14 so negative that tube 1 passes no current. After the desired time delay set by 2P, electrons flow from 6 through tube 1, 7R and 2R to 9. This flow through 2R produces a voltage that charges 2C so that 17 is perhaps 70 volts more negative than 9; this voltage across 2C does not become less than 20 or 30 volts during the half cycle when tube 1 passes no current (for the time constant of 2R and 2C is 0.01 sec, or $\frac{6}{10}$ cycle). This voltage across 2C holds grid 18 so negative that tube 2 no longer passes anode current. Therefore, when tube 1 passes current, the resulting voltage across 2C prevents further flow through tube 2; CR drops out, opening the CR contact.

* A grid bias is a voltage, usually d.c., which keeps a tube from passing anode current; a "turn-on" signal may overcome this bias.

Notice that anode current flows in tube 1 only when 9 is more positive than 6; anode current flows through tube 2 only when 9 is more negative than 6. The voltage across 2*R* caused by tube 1 is stored in 2*C* and a half cycle later is used to control tube 2.

Questions

1. If a resistor burns open in Fig. 6*A*, and this decreases the time delay, which resistor is open?

2. In Fig. 6*F*, when does tube 2 have the largest grid voltage? (*a*) Before the starting contact closes. (*b*) After *CR* picks up.

True or false? Explain why.

3. When switch *S* closes in Fig. 6*A*, the current flowing in 1*R* reverses direction.

4. Grid current flows whenever anode current flows.

5. Alternating voltages and direct voltages both may appear in the same grid circuit.

6. In Fig. 6*A*, when anode current flows in tube 1, part of this current may flow in 1*R* also.

7. In Fig. 6*E*, both tubes may pass current at the same instant.

CHAPTER 7

KINDS OF HIGH-VACUUM TUBE

In the preceding chapters we have used certain high-vacuum tubes in circuits to show how the diode acts as a rectifier, and how the triode[3-1] can be controlled by its grid. Industrial electronic circuits often use tubes having two or three grids, and called *tetrodes*, *pentodes* or *beam power tubes*. Such tubes work much like triodes, in that one grid controls the amount of anode current; the extra grids merely give the tube better performance. To learn the reason for these extra grids, let us first get a better picture of the flow of electricity within a simple diode and triode.*

7-1. Electric Flow in a High-vacuum Rectifier Tube.†—Electric current flows through the space within a tube because great quantities of electrons (tiny particles of electricity) are emitted or "boiled out" of the tube's hot filament, or cathode; many of these electrons pass across to the anode. This flow of electrons is prevented if the anode is at a considerably more negative potential than the cathode (or here we say that the anode is negative). If this tube's anode (see Fig. 7*A*) is made, say, 75 volts more positive than its cathode, enough electrons may pass across to the anode so that the meter shows a current flow of 6 milliamperes. If the anode voltage is now raised to 150 volts, the more positive anode attracts so many electrons that the current

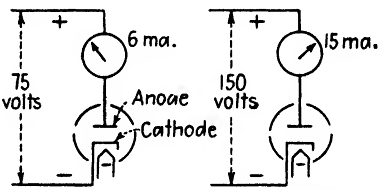


FIG. 7*A*.—Greater anode voltage increases the tube current.

* In most texts on electronics, many chapters are devoted to these tubes and their characteristics, to assist in their selection and circuit design. All that is intended here is to outline briefly the main advantages of each tube type. Most industrial electronic circuits can be well understood, even without the tube details that are given in this chapter.

† The type name for such a high-vacuum diode tube is a *kenotron*.

flow increases to perhaps 15 ma. In the usual operation of such a tube, many more electrons are available at the hot cathode; only part of them pass across to the anode. We may ask why the rest of the electrons do not likewise pass across to the anode and further increase the meter indication; something seems to be limiting the amount of electron flow.

7-2. Space Charge.—When the electrons come out of the hot cathode, they fill the space near the cathode like a tiny cloud. Since these electrons are negatively charged particles, the clouded space near the cathode quickly acquires a negative potential or charge; this *space charge* repels those additional electrons just coming out of the cathode, so that they return back into the cathode. Meanwhile, the anode (if it is positive) attracts electrons from this cloud near the cathode; for each electron that flows from the cloud to the anode, a replacing electron from the cathode is permitted to join the cloud. In this way, the amount of electron flow within the tube increases as the anode is made more positive.

Since electrons flow through the tube only when the anode is more positive, this shows that electrons are attracted to a more positive potential, so the electrons must be negatively charged particles (since we know that positive repels positive, but positive attracts negative).

7-3. The Control Grid.—When a grid is added (as previously described[3-1]) the resulting triode acts quite like the rectifier tube above as long as the grid is connected to the same potential as the cathode. However, if the grid is at some other potential, this affects the electron flow. The metal grid structure is located close to the cathode and close to the cloud of electrons surrounding it; therefore, a small change of potential at the grid (while the cathode potential remains fixed) will cause a large change in the stream of electrons flowing to the anode. In the example shown in Fig. 7*B*, the anode current is 15 ma when the grid voltage is zero (or the grid is at the same potential as the cathode). When the grid is made 4 volts more negative than the cathode, the grid helps

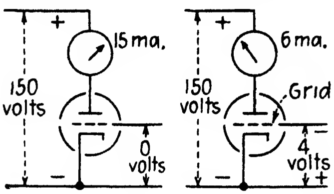


FIG. 7*B*.—More negative grid potential decreases the tube current.

the space charge to repel electrons back into the cathode, so that fewer electrons cross to the anode; the anode current drops to 6 ma. Notice that 4-volts change of grid voltage (Fig. 7*B*) reduces the anode current by the same amount as when the anode voltage is reduced 75 volts (Fig. 7*A*).

7-4. Controlling a Triode.—The complete diagram of a three-element, or triode, tube is shown in Fig. 7*C*, as it appears in a tube handbook or manual.* In Fig. 7*B* and the preceding chapters, we show a simpler diagram for such a triode, using only a circle containing the three tube elements—anode, cathode and grid; the simpler tube diagram or symbol is all that we need in such an elementary circuit diagram, which is used mainly for circuit study. In contrast, a complete wiring diagram of the same circuit must include all connections to the tube socket, as shown later in Fig. 8*B*. Moreover, Fig. 7*C* shows that this certain triode has six base pins, arranged so that this tube may fit into a standard eight-pin or octal socket.†

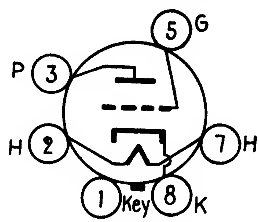


FIG. 7*C*.—Diagram of a triode tube.

To show how a change of anode voltage or of grid voltage will affect the amount of anode current of a tube, the tube manufacturer gives us a set of characteristic curves. Such curves are used in Sec. 3-10 and are shown again in Fig. 7*D*. Here anode or plate current is plotted (vertically) against grid voltage; each slanting line represents one value of anode voltage. When this tube in Fig. 7*D* has 200 anode volts and -4 grid volts (so that the anode is 200 volts more positive than the cathode, and the grid is 4 volts more negative than the cathode), the resulting anode current is shown to be 11 ma (see point *T* in Fig. 7*D*). At this same 200-volts anode, if the grid voltage is changed to -10 volts, the anode current decreases to about 2 ma (point *U*).

* Refer to "Receiving Tube Manual" (RCA, RC-14 or General Electric Company MAQ-37).

† In Fig. 7*C*, pins are missing at positions 4 and 6; the No. 1 pin connects to the metal shell or envelope of this tube. To make sure that this tube is placed correctly into the eight-hole socket, a "key" projects from one side of the tube stem, to fit a similar opening in the socket. Earlier tube sockets, with four to seven holes, receive tubes in only one position. Similar tube details are discussed by W. D. Cockrell, in "Industrial Electronic Control," Chap. 6, McGraw-Hill Book Company, Inc., New York, 1944.

Notice how a change of anode voltage affects the tube current. Starting with point T, if we now decrease the anode voltage to 100 volts, but keep the grid at -4 volts, we must follow down the vertical line to W, where we see that the new anode current is only 2 ma. In this way, these curves show that this tube, a triode, is affected by changes of anode voltage. This decreases the useful output of the tube, as next described.

7-5. The Load Line of a Triode.—In most tube circuits, any change in anode current causes a change in anode voltage.

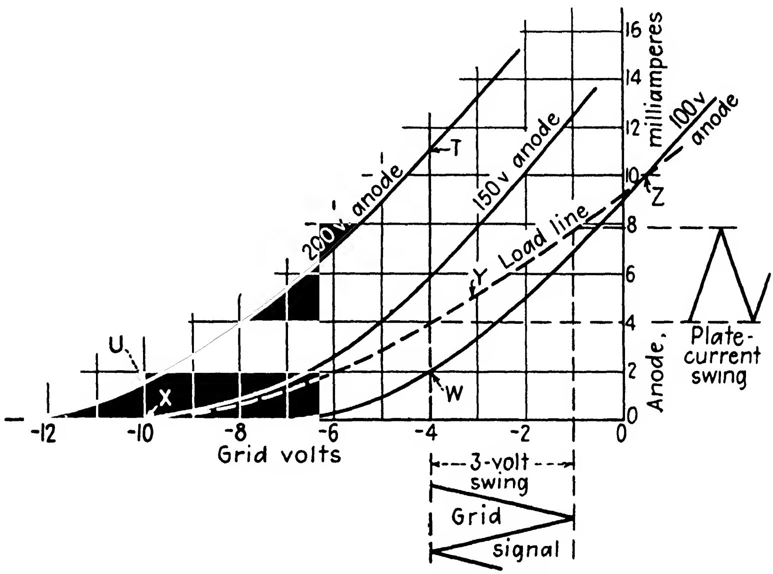


FIG. 7D.—Performance curves of a triode.

For example, in Fig. 7E, when there is no anode current, there is no voltage drop across the coil of relay CR, so the anode voltage A is 150 volts. However, when the anode current is 10 ma or 0.010 amp, there is a voltage drop across CR coil equal to 5000 ohms $\times$ 0.010 amp = 50 volts; the anode voltage remaining at A is, therefore, 150 volts $-$ 50 volts drop = 100 volts. Let us place this information on Fig. 7D.

In this example, zero anode current, together with 150 anode volts, is obtained when the grid voltage is -10; here the tube is seen to be operating at point X in Fig. 7D. When carrying anode current of 10 ma, the anode voltage is only 100 volts, so

the tube is operating at point Z. If we draw a new line (dotted) from X through Y to Z, this *load line* shows the anode current at various grid voltages when this tube is in series with a load resistance of 5000 ohms.* We will next use this load line to find the amount of the "gain" of this tube.

7-6. Gain of a Tube.—We need to learn what anode voltage swing (or change in voltage across the anode load CR) can be produced when we cause the grid voltage to swing or change by 1 volt. Referring to Fig. 7D, the input signal at the grid changes from -1 volt to -4 volts, giving a swing of 3 volts. As a result, the tube's anode current decreases from 8 ma to 4 ma. When 8 ma passes through the load resistance CR of 5000 ohms, the voltage drop across CR is 40 volts; when this current decreases to 4 ma, the voltage across CR is only 20 volts. The change from 40 volts to 20 volts is a swing of 20 volts. Since this 20-volt swing of anode voltage is caused by a 3-volt swing of grid voltage, we say that the "gain" of this tube is 20 volts/3 volts, or 6.3.

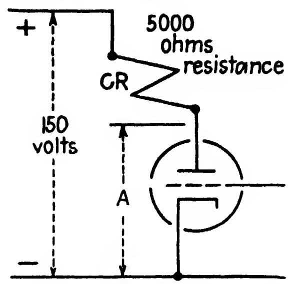


FIG. 7E. Greater tube current lowers anode voltage A.

In most electronic circuits we need to obtain a large gain, thereby greatly increasing the strength of the incoming signal. The power that operates a relay or a loud-speaker may be many thousand times greater than the power that controls the grid of the first tube—a gain of several thousand. To obtain this total gain with the least number of tubes, we naturally prefer a tube that has gain greater than the 6.3 calculated above. To increase this tube gain we must redesign the tube so that a change of anode voltage cannot affect the amount of anode current.†

* A different load line must be used if the load is changed from 5000 ohms. Such a dotted line is a *dynamic-characteristic* curve of the tube, whereas the solid lines are called *static-characteristic* curves.

† In a triode, a change of anode voltage not only affects the anode current, but may also cause objectionable change in the tube's own grid potential. Since the anode and the grid are merely two layers of metal separated in space, they act like a small capacitor; a quick rise in anode voltage causes, by this capacitor action, a small rise of grid potential. Such "feedback" from the anode to the grid must be avoided in many circuits, as in radio, which operate at high frequency. The usual remedy is the addition of the screen grid, described in Sec. 7-7.

The ideal tube design would, therefore, have a performance or characteristic curve like Fig. 7*F*; here, at a constant grid voltage of -6 volts, the anode current remains at 8.5 ma, whether the anode voltage is 25, 75, 150 or 300 volts. Only a different grid voltage will change the anode current. In contrast, see how the slanting characteristic curves of a triode* (in Fig. 7*G*) quickly show that tube anode current increases as anode voltage increases. Nevertheless, the triode is a simple and rugged

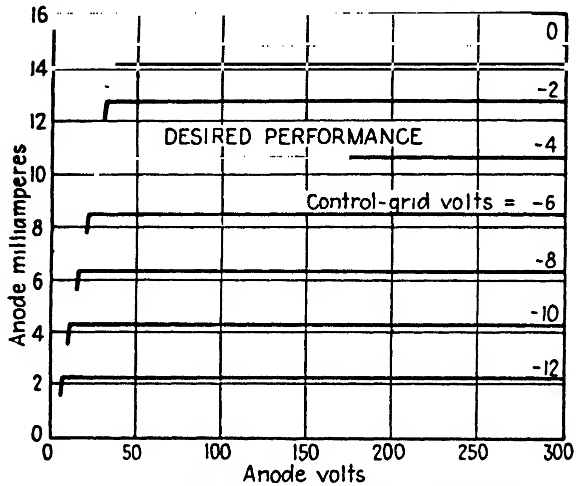


FIG. 7*F*.—Performance curves of an ideal tube.

tube, and is often found in industrial circuits. We shall see triodes used in Figs. 8*A*, 8*G* and 8*H*.

7-7. The Tetrode. Adding the Screen Grid.—The performance of a high-vacuum triode is brought much closer to the ideal curves of Fig. 7*F*, if a second grid is built into the tube. The result is seen in Fig. 7*H*. This extra grid is made of metal mesh, which nearly surrounds the anode; it is called the *screen grid* because it screens or separates the anode away from the rest of the tube. Having four elements—cathode, anode and two grids—this tube is a *tetrode*. Figure 7*I* shows the symbol for a tetrode and the arrangement of the tube parts.

The screen-grid connection, at a base pin of the tube, is usually wired to a point in the circuit which is kept constant, per-

* The curves of Fig. 7*G* give the same information as the curves of Fig. 7*D*, but in different form.

haps 90 volts more positive than the cathode. Even though the tube's anode voltage may change, the screen-grid voltage remains unchanged. The steady positive potential of the

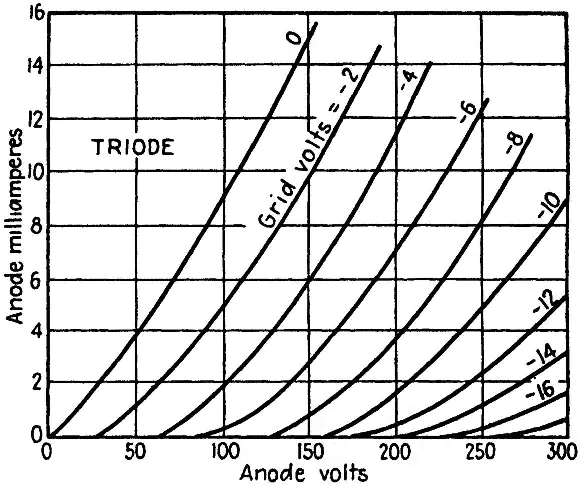


FIG. 7G.—Anode performance curves of a triode.

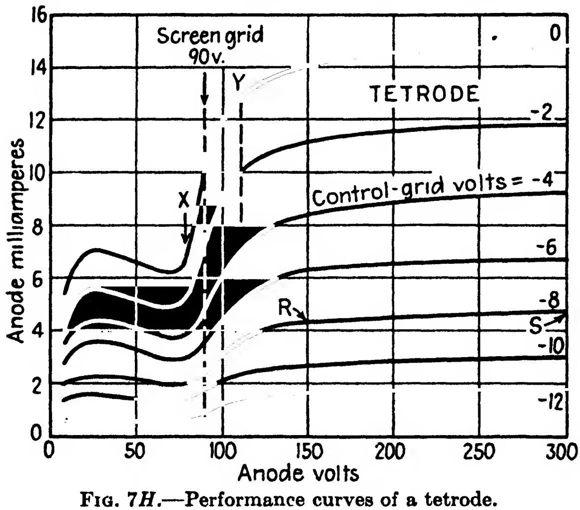


FIG. 7H.—Performance curves of a tetrode.

screen attracts the electrons directly from the cathode; these electrons are not affected by the anode potential until they have passed the screen. Although the wires of the screen grid are spaced close together, most of the electrons pass from the

cathode through the screen to the anode. The quantity of electrons flowing to the anode now depends mainly on the constant screen voltage and, of course, the control-grid voltage. In Fig. 7*H*, using the line marked −8 (grid held constant 8 volts more negative than the cathode), we see that the plate or anode current is 4.5 milliamperes at point *R*, when the anode voltage is 150; the anode current increases only to 5.0 ma at point *S*, when the anode voltage is 300. (In contrast, Fig. 7*G* shows that a triode's current might increase from 1 ma to 15 ma.)

Although the tetrode approaches the desired results (of Fig 7*F*) at high anode voltages, the left-hand part of Fig. 7*H* shows undesirable results if the anode voltage becomes less than the screen-grid voltage. Notice that only half as much anode current flows at *X* (80 volts anode) as compared to *Y* (110 volts anode). At *X*, the anode is less positive than the 90-volt screen grid, so the electrons naturally prefer to collect at the screen grid; more electrons flow to the screen grid, fewer flow to the anode. This "robbing" of anode current is made possible by secondary emission, which must be overcome before we can get our "perfect tube."

7-8. Secondary Emission.—When electrons are attracted toward a point of higher potential (such as a more positive anode), the electrons gain high speed and strike the anode with such force that they "splash"; some of the electrons bounce back, or we say that, because of this collision, other electrons are driven out of the cold anode material; the electrons produced at the anode in this way are caused by "secondary emission," and are emitted only because of the energy released by the arrival of electrons from the cathode.

In the screen-grid tube, most of the high-speed electrons from the cathode miss the screen grid and strike the anode, even when the anode is less positive than the screen. However, the rebound or secondary electrons drift back to the screen grid and are lost from the anode current at *X*, as was mentioned above. Without a screen grid (as in a triode), or when the anode voltage is to the right of *Y* in Fig. 7*H*, the secondary electrons have nowhere to go except back into the anode.

7-9. The Pentode. Adding the Suppressor Grid.—To overcome this effect of secondary emission in the screen-grid tube, so that it may work better at very low anode voltages, a third

grid is built into the tube and is placed between the anode and the screen grid. Having five elements—cathode, anode and three grids—this tube is a *pentode* and is shown in Fig. 7J. The third grid is called the *suppressor*, because it suppresses or stops the flow of electrons from the anode to the screen grid. This suppressor grid is usually connected to the cathode (either

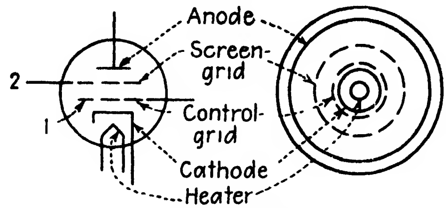


FIG. 7I.—Symbol and arrangement of a tetrode.

inside the tube, or by an external circuit); therefore, it has a more negative potential than either the anode or the screen grid. Any electrons that bounce or are emitted from the anode, as described above, are repelled by the negative suppressor grid and return to the anode, instead of traveling to the more positive screen grid. Figure 7K gives the result—horizontal lines showing very little change in anode current, although the anode voltage may swing down to values below 100 volts. Here,

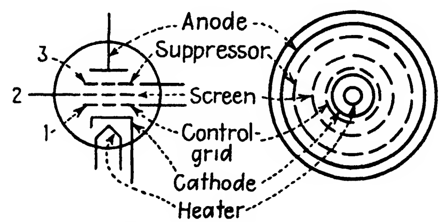


FIG. 7J Symbol and arrangement of a pentode

then, is a tube having very high amplification factor, a tube which gives high gain. Its control grid (or No. 1 grid) has complete control of the amount of anode current; the other grids help to make this possible.

Pentode tubes are shown in the circuits of Fig. 10A and Chaps. 17 and 22. In each of these circuits, you will see that the pentode is controlled only by that grid nearest the cathode; the other grids are connected to voltage dividers or similar constant-

potential points. In later circuits such as Fig. 23C, separate signals are applied to both the screen and control grids; either grid voltage may control the anode current.

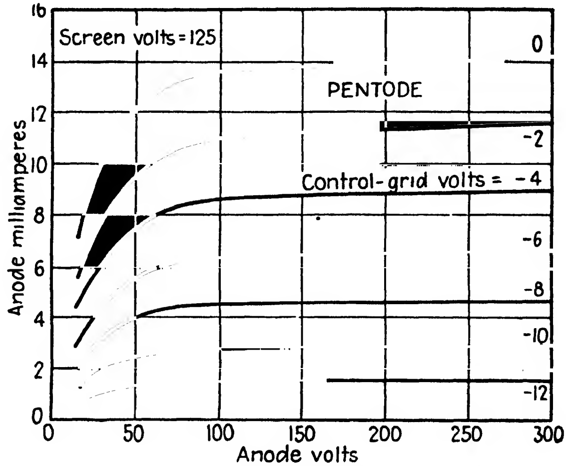


FIG. 7K.—Performance curves of a pentode.

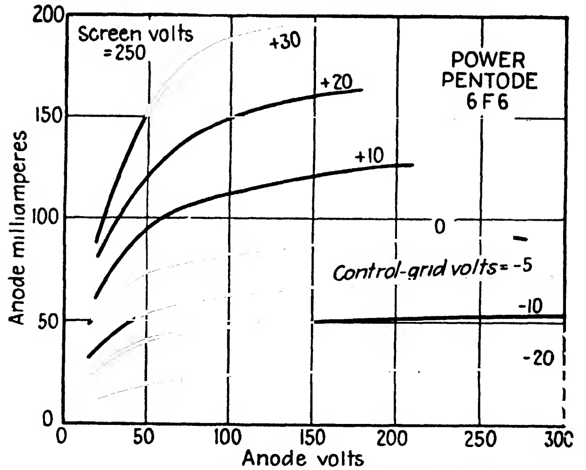


FIG. 7L.—Performance curves of a power pentode.

When a pentode is used to give high gain in voltage and low anode current, notice that the pentode lines of Fig. 7K are nearly the same as the "perfect-tube" lines in Fig. 7F. However, when the pentode is used as a power amplifier (with greater

anode current, as shown in Fig. 7L) the pentode lines become more curved; we see that the pentode is not ideal for delivering large power output when the anode voltage must swing down to 40 or 60 volts. To meet this need we now come to the beam power tube.

7-10. Beam Power Tube.—Any certain size of screen-grid tube can be made to produce and control greater power output if we add beam-forming plates instead of a suppressor grid. As shown in Fig. 7*M*, these beam-forming plates are solid sheets of metal connected to the cathode inside the tube; these plates

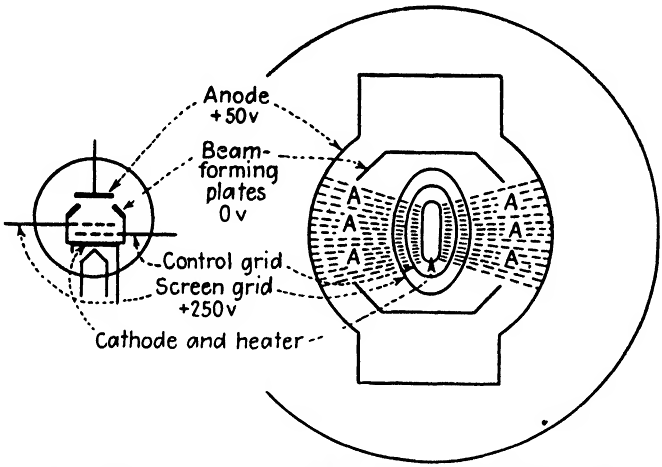


FIG. 7*M*.—Symbol and arrangement of a beam power tube.

prevent electrons from flowing to the anode except through the two shaded portions, or beams. Looking at these same tube parts from another direction, Fig. 7*N* shows that the electrons pass in beams (shaded) between the wires of the control grid. Since each wire of the screen grid is carefully located directly behind a control-grid wire, very few electrons ever strike the screen grid. Nearly all the electrons reach the anode or plate, where they may "bounce" or cause secondary emission. These electrons might be attracted back to the more positive screen grid; to prevent this, the beam-forming plates are at zero, or cathode, potential and are carefully shaped so that they spread this zero influence through the zone or space marked *A* in Fig. 7*M* or 7*N*. These plates act like a suppressor grid, without

having grid wires scattered in the path of the electrons. Any electrons wandering away from the anode are repelled by this zero zone A. The result (for a tube of the same size as in Fig.

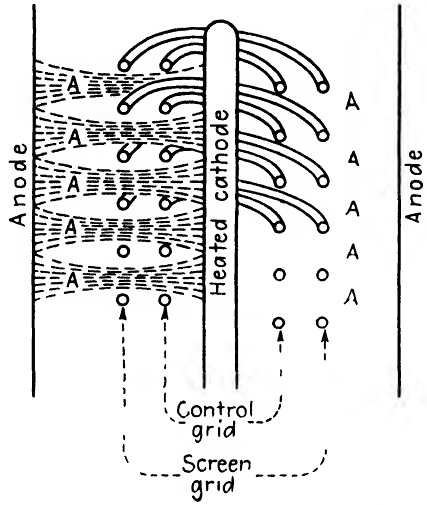


FIG. 7N.—Grid wires in a beam tube.

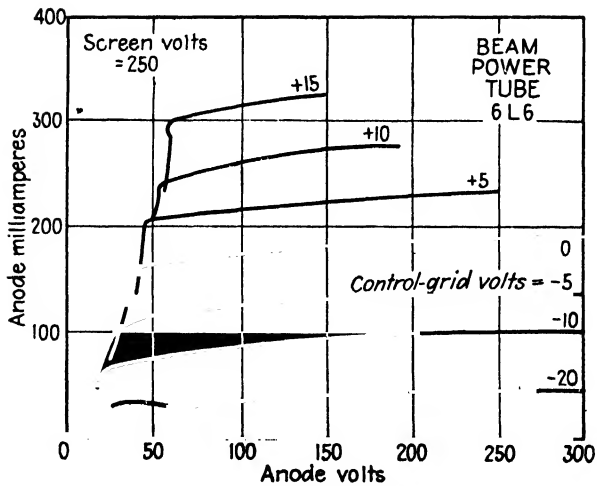


FIG. 7O.—Performance curves of a beam power tube.

7K or 7L) is shown in Fig. 7O, where, even at anode currents as large as 100 to 300 ma, the anode voltage is seen to have little effect on the amount of current in this beam power tube.

Having an anode, cathode and two grids, the beam power tube is a tetrode; the beam-forming plates are not counted as separate tube elements. Ordinary tetrodes[7-7] are now little used, having been generally replaced by pentodes or beam tubes. You will find beam tubes in the circuits of Figs. 8*D* and 10*E*. The tube in Fig. 4*H* is shown as a triode, but the tube used in this airplane time relay is really a beam tube; notice that we understand that circuit operation, regardless of which type of tube is used.

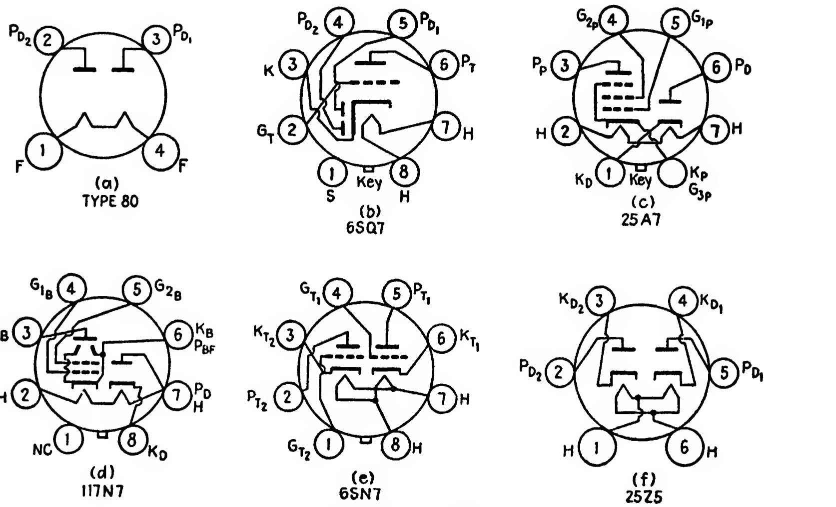


FIG. 7*P*.—Duplex tubes.

7-11. Duplex Tubes. Several Tube Operations in One Enclosure.—In the preceding paragraphs we have called an electron tube by its name of diode, triode, tetrode or pentode, depending upon the number of grids in the tube; each one of these tubes is complete in itself, having one anode and one cathode. Two or more of these complete anode-cathode-grid assemblies are often placed inside one glass or metal enclosure or envelope; here they may work like two or more separate tubes, but they share a single base and socket. Such a combination is called a *duplex tube;* physically it is just one tube, and all its parts are shown inside one circle in the complete tube diagram. In the several examples of duplex tubes shown in Fig. 7*P*, you quickly recognize (*a*) two diodes combined in

one enclosure, as described in Sec. 2-10, and called a duo-diode, or a *full-wave rectifier; (b) two diodes and a triode, all using* the same cathode (type 6SQ7). Similarly (*c*) shows one diode combined with one pentode, each having its own separate cathode (type 25A7,* called a *rectifier pentode*). In these duplex tubes, the stream of electrons flowing to one anode is entirely separate from the stream of electrons flowing to another anode, even though both electron streams may be emitted from one common cathode; in (*b*) of Fig. 7*P*, the grid control of the triode portion has no effect upon the electron flow of either diode.

A duplex tube merely combines those tube operations that often occur together in various circuits, such as in radio receivers; instead of using several simple tubes, a single duplex tube saves space and cost. This same idea applies to a doctor and a dentist who combine their offices so that, while each has his own work space and patients, they share the rent, heat and waiting room.

In (*d*) of Fig. 7*P*, the rectifier-beam-power amplifier acts separately as a rectifier and as a beam power tube; notice that its two filaments, in series, have no electrical connection to either cathode. This tube (117N7) is shown in a complete wiring diagram of a photoelectric relay in Fig. 8*B*; later, we shall study this photoelectric relay, using the elementary diagram of Fig. 8*C*. In Fig. 8*C* notice that this 117N7 tube is shown as two separate tubes—a diode in one part of the circuit and the beam power tube in another portion of the diagram.

The twin triode of (*e*) is used later as two separate triodes (tubes *C* and *CC* in Fig. 24*C*, type 6SN7).

The twin diode of (*f*) in Fig. 7*P*, has separate cathodes; this tube (type 25Z5) is a rectifier doubler, intended to do the same work as the two separate tubes shown in the voltage-doubler circuit of Fig. 5*G*.

7-12. Special Tube Types.—The tubes already described are for general-purpose use; they are found in a great variety of industrial and communication circuits. Many other tubes have more limited use or are made specially for one certain purpose; more new special types will be used, far beyond the range of

* The first part of this tube number or designation shows the approximate filament voltage used for heating the tube; the 6SQ7 has a 6.3-volt heater, the 25A7 has a 25-volt heater, while the filament or heater of the 117N7 tube operates at about 117 volts.

this book. We have many uses for one special tube, the cathode-ray tube described later.[27-4] This high-vacuum tube has a hot-filament cathode, a grid and several anodes; the stream of electrons passes beyond the anodes and strikes the circular end of the tube, where it causes a spot of light that moves or traces a curve in response to electric voltages applied to other electrodes within the tube.

Questions

1. When a high-vacuum tube is used with a 5000-ohm resistor, with a 200-volt supply, what is the greatest expected anode current?

2. Suppose that a 100,000-ohm resistor is in series with the grid of a tube, and the grid signal voltage is always negative. If a 1-megohm grid resistor is substituted, what is the change in tube operation?

3. If the anode current is 10 ma when the screen grid is at +200 v, what is the anode current if the screen grid is at 0 volts (while the anode voltage and control-grid voltage remain unchanged)?

a. 10 ma?
b. 3 ma?
c. Zero or negligible?

4. How many separate electron streams may flow in a duodiode-pentode when the control-grid potential is

a. +20 v? *b.* −20 v?

True or false? Explain why.

5. In sizes used in radio receivers, an anode current of ¼ ampere is within the operating range

a. of a triode.
b. of a beam tube.

6. Grid voltage depends on the filament current.

7. A suppressor-grid tube is used instead of a triode, because

a. it responds at greater speed.
b. it has greater useful gain.
c. it does not need a screen grid.

8. When a separate cathode is added to a triode, it becomes a four-element tube or tetrode.

9. The deflecting plates of a beam tube may be connected to anode potential.

10. So that the anode voltage will not disturb the control-grid voltage,

a. a suppressor grid is added.
b. the space charge is removed.
c. a screen grid is added.

11. A diode may be used as an amplifier.

12. The filament of a tube is always at cathode potential.

13. A triode may pass anode current even when its grid is negative.

14. Grid voltage is the difference in electric pressure between the grid and the anode.

CHAPTER 8

LIGHT AND HEAT RELAYS

The use of light rays to control an electric circuit has already been mentioned. The phototube, or "electric eye," is shown in a d-c photoelectric relay (Fig. 3*G*) and again in the a-c relay of Fig. 5*A*. Let us see how this a-c relay is used for turning lights on or off in an office or a schoolroom.

8-1. Room-lighting Relay.—This photoelectric relay, mounted inside the room, "watches" the amount of daylight coming

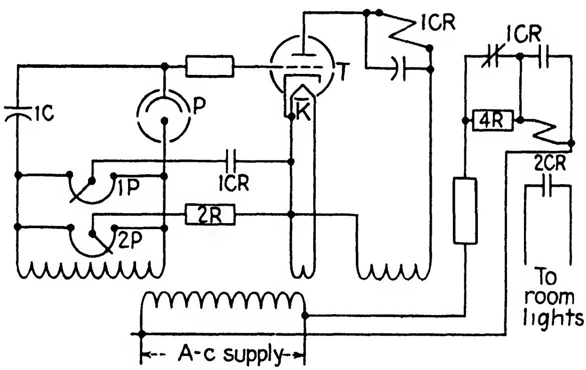


Fig. 8*A*.—Phototube relay to control room lighting.

through the windows; when this daylight becomes less than the desired amount, the relay turns on the electric lights in the room. The illumination provided by these lights also reaches the phototube and immediately turns the lights off again, if we use merely the simple circuit of Fig. 5*A*. Therefore, Fig. 8*A* includes the a-c photoelectric relay of Fig. 5*A*, but uses two potentiometers *1P* and *2P*, together with a larger contactor *2CR* for the light circuit.

When it is dark outside, phototube *P* receives only the light from the electric lights in the room; this is not enough light to make phototube *P* turn on amplifier tube *T*; relay *1CR* is not picked up. Therefore the normally-closed contact ( ) of

$1CR$ has shorted the resistor $4R$; contactor $2CR$ is energized, and the room lights are on. Notice also that another $1CR$ contact is open between $1P$ and cathode K, therefore $1P$ is not affecting the phototube circuit.

When daylight increases, the total light on phototube P increases; when this total light in the room is so strong that the electric lights are not needed, $2P$ is set so that P will pick up relay $1CR$. A contact of $1CR$ shorts around the $2CR$ coil so that $2CR$ drops out, turning off the lights. At the same instant, $1CR$ closes the circuit between K and $1P$ so that the setting of $2P$ no longer controls the phototube circuit; $1P$ is set lower, so that the room light will not come on again until the daylight decreases. With correct settings, $1P$ turns the lights on when daylight is less than say 40 units; if the electric lights provide 50 units, then $2P$ waits until the total light becomes more than 90 units before turning the light off again.

8-2. Connection or Wiring Diagram. Elementary Diagram.—In all the circuits shown this far, the parts of the diagram are arranged so that we can more easily trace and understand the operation of the circuit; such diagrams do not show where the various parts are really located in the complete assembly. These diagrams (of which Figs. 8*A* and 8*C* are examples) are called *elementary* diagrams.

Another kind of diagram is shown in Fig. 8*B*. This is called the *connection* or *wiring* diagram, because it shows the wire connections between the various parts, arranged just as they are when you trace the wires from one part to another. Each part is shown in its proper place, as if you were looking at the bottom or underside of the chassis or frame, holding it so that the six numbered terminals are at the top. You use this connection diagram when making external connections or when locating certain parts. To study how this circuit works, this connection diagram is not suitable; instead, you use the elementary diagram of this same equipment, which is Fig. 8*C*. Such elementary diagrams are shown throughout this book.

However, the connection diagram gives other valuable information. Notice in Fig. 8*B* that only two tubes are used, as shown by the dotted circles. (The inner circle encloses the parts within the tube, the outer circle* represents the tube

* Recent diagrams may omit the outer tube circle.

socket, showing the external connections to the socket terminals.) The left-hand tube (type 117N7) is a duplex tube[7-11] and is represented in Fig. 8*C* by two separate circles, tube 1 and tube 2. We study and understand it as two separate tubes; we locate or replace it as just one tube. The connection diagram shows more quickly the total number of contacts on a relay, or

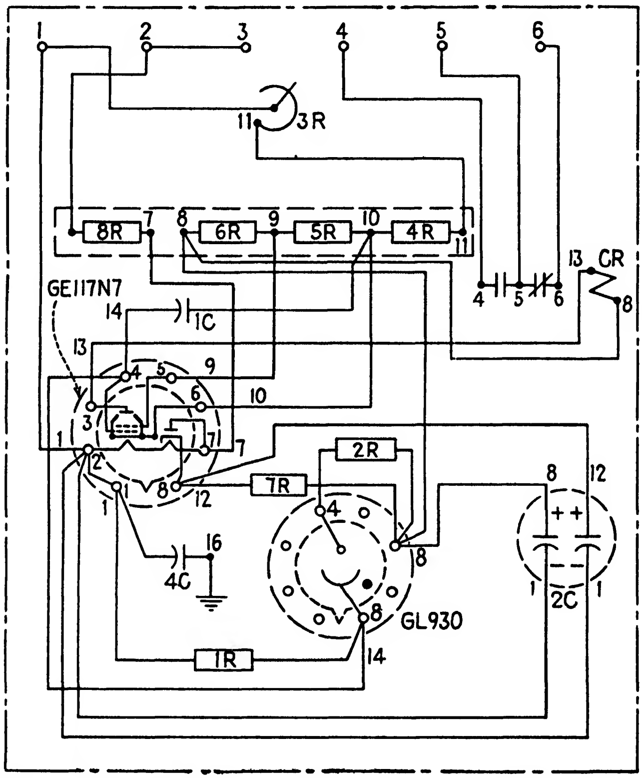


FIG. 8*B*.—Wiring diagram of a d-c, a-c phototube relay (CR7505–K108).

the number of windings on a transformer—these may be widely scattered in the elementary diagram. Most elementary diagrams omit the filament or heater connections to the tube and use only a single cathode connection, as shown in Fig. 8*F* or Fig. 8*G*.

As an electronic equipment becomes more complex, including more tubes and relays, it becomes more necessary to have both the elementary diagram and the wiring diagram available.

Only by combined knowledge and use of both diagrams can proper maintenance or service be given.

A *schematic* diagram (as used mainly in communication electronics) aims to show a circuit in simple form, like an elementary diagram. Unlike the elementary, the schematic shows terminal connections and accessories, and keeps together the windings of each transformer or the parts of each relay; as a result, the schematic loses some of the directness with which a true elementary can be analyzed.

8-3. A D-c, A-c Photoelectric Relay.—Figure 8*C* shows the elementary diagram of a light-sensitive relay that may be oper-

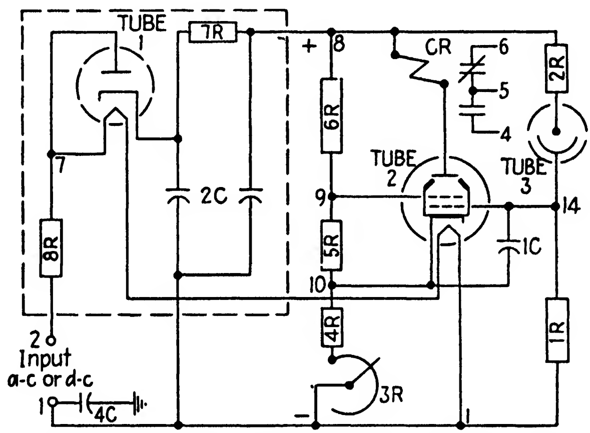


FIG. 8*C*.—Elementary diagram of d-c, a-c phototube relay.

ated from either a-c or d-c power supply. As is explained below, when sufficient light shines on phototube 3, this permits current to flow through tube 2, causing relay *CR* to pick up and operate its contacts to control external circuits.

If points 1 and 2 are connected to a 115-volt a-c supply, the portion of Fig. 8*C* within the dotted line serves to convert this a.c. into a d-c voltage, which appears between points 8 and 1. That is, tube 1 acts as a half-wave rectifier, which permits current to flow through it during only the half cycles when tube-1 anode is positive. Since this tube current flows only in one direction, it charges capacitors 2*C*, which smooth this pulsating tube output into a usable steady d-c voltage; in this way, these capacitors and resistor 7*R* act as a filter (like that described

in Sec. 10-4). However, if points 1 and 2 are connected to a 115-volt d-c supply (with the positive side at point 2), electrons flow steadily through 7*R* and tube 1, and a d-c voltage again appears between points 8 and 1.

In circuits supplied only by a.c., the tube filaments often work at low voltage furnished by a small transformer. Since such a transformer cannot be used in Fig. 8*C* on d-c supply, the tube filaments are designed to operate directly at supply voltage. Tubes 1 and 2 are built in one enclosure,[7-11] using a single socket.

Between points 8 and 1 in Fig. 8*C*, resistors 3*R*, 4*R*, 5*R* and 6*R* merely divide the d-c voltage into usable parts. The flow of electrons which picks up *CR* must pass from 1 through 3*R* and 4*R* to point 10, cathode to anode of tube 2, and through *CR* to 8. This tube current cannot flow when the control grid of tube 2 (at point 14) is considerably more negative than the cathode (point 10), as when the light beam at phototube 3 is interrupted. When phototube 3 is dark, it acts as a very high resistance, much greater than 1*R*, so that the potential of point 14 is close to that of point 1, and therefore is more negative than point 10.

When the light beam reaches phototube 3, this phototube permits enough electrons to flow (from 1 through 1*R* and phototube to point 8) to cause a large voltage drop across 1*R*; this raises the potential of point 14 (grid of tube 2) so as to permit anode current to flow through tube 2 and pick up *CR*. By turning 3*R*-slider clockwise, we increase the amount of light required to operate the relay; we increase the resistance and voltage drop between points 10 and 1, raising the tube-2 cathode to a higher potential. To turn on tube 2 we must now raise its grid 14 to a higher potential also, and this requires more current flow through 1*R* and more light on phototube 3.

In describing the operation of tube 2, we have mentioned only one grid, as though tube 2 were a triode. In Fig. 8*C* the symbol of tube 2 shows that it is a beam power tube—a form of tetrode having deflecting plates, described in Sec. 7-10. This more complex tube gives superior performance but is controlled in the same way as a triode, by means of the potential of one grid close to its cathode. The other grid is connected to point 9, whose potential is not affected by the phototube circuit.

8-4. The Phototroller.—This is a standard form of light-operated relay, as designed by another manufacturer. Its schematic diagram is shown in Fig. 8*D*. When it is rearranged into the corresponding diagram of Fig. 8*E*, we notice that this circuit is quite similar to Fig. 5*A*.

We recognize that current may flow through tube *T* and the coil of contactor *I* only during the half cycle when transformer

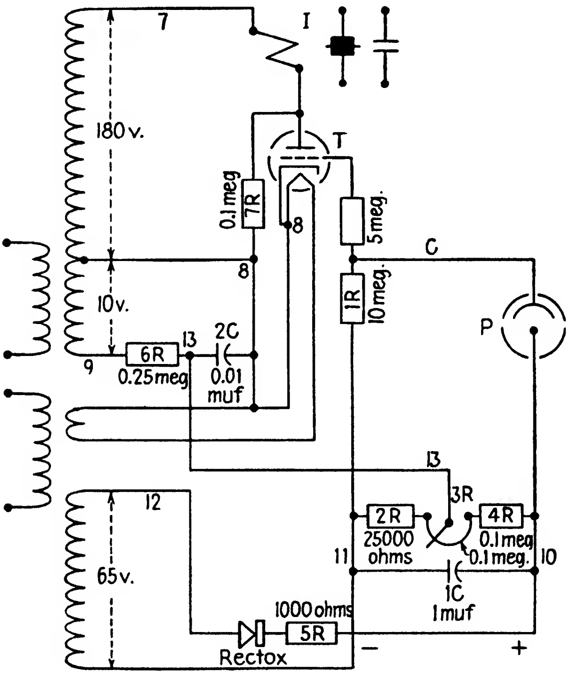


FIG. 8*D*.—Schematic diagram of a Phototroller.

terminal 7 is more positive than terminal 8. During the other half cycle, a very small current flows through resistor 7*R* to prevent contactor *I* from chattering; this 7*R* current is too small to keep contactor *I* picked up unless tube *T* is also passing enough current.

To see what controls tube *T*, study the grid circuit at the left-hand side of Fig. 8*E*. (This will be more easily understood if we place a connection or short circuit from point 13 to point 8, temporarily removing the effect of the 10-volt transformer winding and capacitor 2*C*. The purpose of these parts is explained

later in Sec. 11-7.) Notice that the 65-volt transformer winding may force a large electron flow (when terminal 11 is more negative than 12), through 2*R*, 3*R*, 4*R*, 5*R* and the Rectox (copper-oxide rectifier[28-13]), thereby producing, say, 80 volts drop across 2*R*, 3*R* and 4*R*; capacitor 1*C* becomes charged to this voltage, and its right side is more positive than its left side. During the following half cycle (when 11 is more positive than 12) the Rectox prevents most of the reverse electron flow, which might discharge capacitor 1*C*. Capacitor 1*C* is so

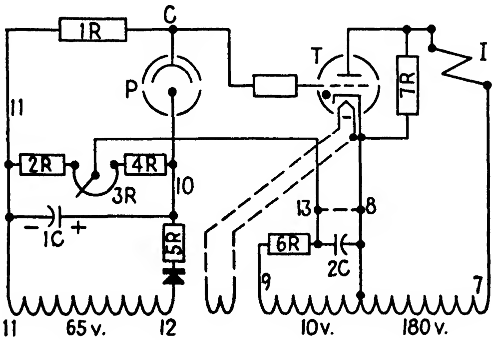


FIG. 8*E*.—Elementary diagram of a Phototroller.

large* that the d-c voltage across it is quite steady; this d-c voltage is also applied across 1*R* and phototube *P* in series.

When *P* is dark, there is so little electron flow through 1*R* and *P* that most of the 1*C* voltage appears across *P* and very little across 1*R*; therefore, the potential at *C* (grid of tube *T*) is close to the negative side of 1*C* and prevents tube *T* from firing or passing anode current. When more light strikes *P* and increases the electron flow through 1*R* and *P*, the voltage drop across 1*R* increases, raising the potential at *C* until tube *T* passes current to pick up contactor *I*.

When the slider of 3*R* is turned to touch the end near 4*R*, the entire voltage across 2*R* and 3*R* is used to bias or make the grid of *T* negative; therefore, a large amount of light must reach *P* before the voltage across 1*R* is large enough to turn on tube *T*.

* Capacitor 1*C* (1 microfarad) tries to discharge through 2*R*, 3*R* and 4*R*, which total 225,000 ohms or 0.225 megohms. The time constant[4-5] is 1 (mu f) × .225 (megohms) = 0.225 sec; therefore, during about 1/100 or 0.01 sec between the impulses of charging current, 1*C* loses very little of its charge or voltage.

When the $3R$ slider is turned to the left or $2R$ end, only the voltage across $2R$ keeps the grid of T negative, so tube T picks up I at very small amounts of light.

Notice that grid rectification[5-4] is not used in this circuit to produce the d-c voltage across $1C$; the Rectox is used instead.

8-5. Flame-failure Control.—Various electronic devices are used to shut off the fuel supply if the furnace flame fails.* Certain luminous flames may be detected by a phototube, and Fig. 8*F* shows a circuit for phototube flame detection. Light from the flame falls on phototube P, which permits transformer

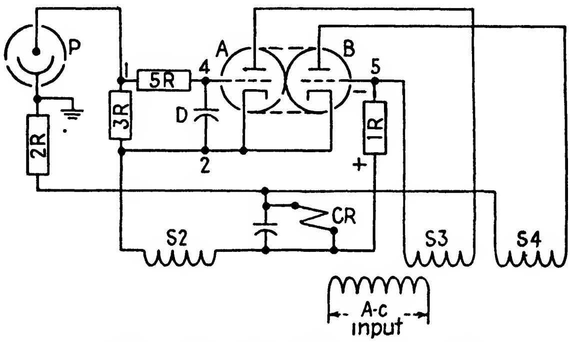


FIG. 8*F*.—Phototube relay for flame control.

secondary $S2$ to force a tiny flow of electrons through relay coil CR, and through $2R$, P and $3R$; this flow causes a voltage to appear across resistor $3R$. Capacitor D charges to this voltage, which keeps the grid 4 of tube A more negative than its cathode 2. Since this negative grid prevents any anode current through tube A, no current flows through $1R$ (traced later). With no voltage drop across $1R$, the grid 5 of tube B is more positive than its cathode 2 (because of the voltage of transformer $S2$) during the half cycle when all the transformer secondaries are positive on the right-hand side. Therefore, there is a large flow of electrons from point 2 to tube-B anode, through $S4$, relay coil CR, and $S2$ back to 2. Notice that the voltages of $S4$ and $S2$ combine to force current to pick up relay CR, permitting fuel to flow to the flame. Tube B controls this current flow.

When the flame fails, no light reaches P, so no current flows through resistor $3R$. After a very short delay (while capacitor D

* Flame-failure Control of Industrial Furnaces, *Electronics*, September, 1944, p. 152.

discharges through $3R$ and $5R$), the grid of tube A approaches the same potential as cathode 2; electrons flow from cathode 2 to anode of tube A, through $S3$, $1R$ and $S2$, back to 2. (Here the voltages of $S2$ and $S3$ add, to cause these electrons to flow through $1R$.) The resulting voltage appearing across $1R$ makes point 5 (grid of tube B) more negative than cathode 2, so the tube-B anode current decreases and CR drops out, shutting off the fuel.

8-6. The Protectoglow.—Another method of flame detection makes use of the tiny current that may flow through the flame itself. An average flame has from 2 to 100 megohms resistance;

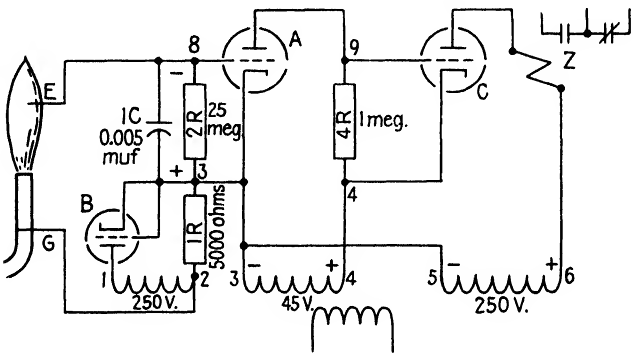


FIG. 8G.—Protectoglow circuit for flame detection.

the resistance of the unlighted fuel is much greater. If an electrode is placed in the flame (at E in Fig. 8G) several millionths of an ampere may flow between clamp G and electrode E. This current is too small to operate anything but an electronic circuit. We shall see that a normal flame will "turn off" tube A, "turn on" tube C and pick up relay Z, to feed fuel to the flame.

Tube B works only in the grid circuit of tube A.* During the half cycle when transformer terminal 1 is more positive than 2, electrons flow through $1R$ and tube B. If there is normal flame, additional electrons flow from 2, through the flame from G to E, returning through $2R$ and tube B to point 1. Notice that $2R$ is a 25-megohm resistor, so only one microampere of current causes 25 volts drop across $2R$; this voltage across $2R$ charges capacitor $1C$ also. During the next half cycle (when tube B can-

* A schematic or wiring diagram shows tubes A and B in one enclosure, as a twin triode.[7-11] The grid and the cathode of tube B are connected together, so this triode acts like an ordinary rectifier or diode.

not pass current), 1*C* tries to lose its charge by forcing electrons through the flame and 1*R*; since this total resistance is at least 2 megohms, we realize that 1*C* (0.005 mu f) retains much of its charge during the next half cycle (for the time constant[4-5] is 0.01 sec, longer than a half cycle). This voltage across 1*C* keeps the grid of tube *A* more negative than cathode 3. Therefore, tube *A* has no flow of anode current, so there is no voltage drop across resistor 4*R*; the grid 9 of tube *C* is at the same potential as cathode 4, so tube *C* passes current to pick up relay *Z* and feed fuel to the flame.

When the flame fails, no current flows through resistor 2*R*, so grid 8 rises to the same potential as cathode 3 and turns on tube *A*. Electrons flow from cathode 3 to anode 9 and through resistor 4*R*; the resulting voltage drop across 4*R* makes point 9 (grid of tube *C*) more negative than cathode 4, so anode current stops, dropping out relay *Z* to shut off the fuel.*

If electrode *E* is out of adjustment and touches the nozzle, this makes a circuit from *G* to *E*, as though there were a flame. Notice how tube *A* "ignores" such a false signal. If *E* touches *G*, electrons flow through 2*R* and charge 1*C*, as was described above. However, during the next half cycle, 1*C* discharges almost instantly by forcing electrons through the shorted electrode and resistor 1*R*. The resistance of this discharge path is only 5000 ohms, instead of the 2-megohm flame. Therefore, 1*C* has already lost its charge when the anode of tube *A* becomes positive during the following half cycle; tube *A* passes current, as it does when there is no circuit of any kind between *E* and *G*.

8-7. A Temperature Indicator.—In the circuit of Fig. 8*H*, phototube *X* "looks at" white-hot metal and makes an indicator move up or down scale as the temperature of this metal changes. The current that moves the indicator also passes through a lamp *L*; when a large current makes the indicator point at a high temperature, this same current makes lamp *L* brighter, so that more light shines on another phototube *Y*.

At the bottom of Fig. 8*H*, tube *A* is a rectifier, which changes

* Notice that relay *Z* could have been moved into the anode circuit of tube *A* (in place of 4*R*), a flame failure then must pick up *Z*, using its normally-closed contact to shut off the fuel. This arrangement does not "fail safe," for the fuel is not shut off if coil *Z* or the power supply fails. If tube *C* is added, safer operation results.

the a-c supply S into a d-c voltage that is positive at point 15, negative at 12. Resistors $1R$, $2R$ and $3R$ divide this voltage into usable parts. Similarly, tube B produces another d-c voltage, positive at point 18, negative at 16; this voltage is divided by $5R$ and $6R$. These d-c voltages are smoothed or filtered by combinations of capacitors and reactors or chokes, as is explained in Sec. 10-4.

The cathode of tube C is at a fairly constant potential 13; however, the grid of tube C is controlled by phototubes X and Y. Notice that these phototubes are connected in series across the

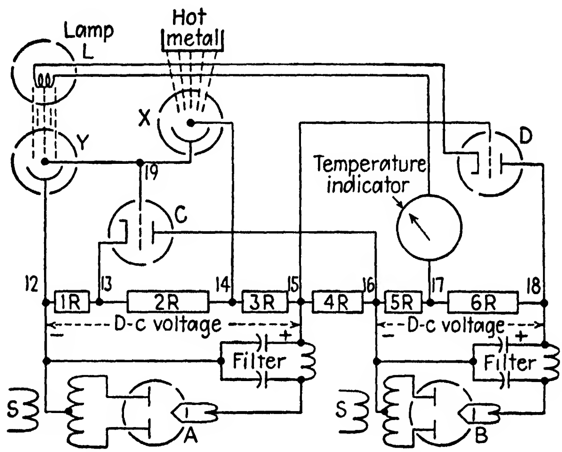


FIG. 8H.—Temperature-indicator circuit.

constant voltage 14 to 12. Each phototube acts like a variable resistor; if the light reaching X increases, the resistance of X decreases.

Let us start with cold metal, giving no light to phototube X. We shall see that lamp L also is dark, giving no light to phototube Y. Here both X and Y have high resistance; since their resistances are about equal, the potential at point 19 is midway between points 14 and 12. Because $1R$ has more ohms resistance than $2R$, the potential at 13 (cathode of tube C) is much more positive than 19 (grid), so that tube C passes no current. As a result, there is no voltage drop across resistor $4R$ (since the only electrons that can flow through $4R$ must pass from point 13 through tube C and through $4R$ to point 15).

Meanwhile, the cathode of tube *D* is at the same potential as point 17 (for there is no current or voltage drop in lamp *L* or the indicator). The tube-*D* grid 15 is at the same potential as point 16 (remembering that there is no voltage drop across $4R$); however, the voltage across resistor $5R$ acts as a bias, which keeps tube-*D* grid more negative than point 17 (cathode), so that tube *D* passes no current, and the indicator points at the lowest temperature.

As the metal temperature rises, more light strikes *X*, decreasing its resistance (while the *Y* resistance is yet unchanged). This immediately raises the potential of tube-*C* grid, so that current flows through tube *C* and $4R$; this current makes point 15 more positive than 16, raising the potential of tube-*D* grid. Tube *D* now permits electrons to flow from point 17 through the indicator and lamp *L*, through tube *D* to point 18; the indicator reads higher on the scale, the lamp *L* becomes brighter. As more light from *L* reaches phototube *Y*, the resistance of *Y* decreases, to match more closely the resistance of *X*; the whole circuit quickly steadies at a condition where *X* resistance is just enough less than *Y* resistance, so that tube *C* passes enough current to make tube *D* pass enough current to cause lamp *L* to give just enough light to hold the tube-*C* grid at the required potential.

You see, this is an endless chain of events, and that is the reason why this kind of circuit is called a *feed-back* or *self-regulating* circuit.

8-8. Other Light and Temperature Relays.—Many photoelectric or temperature relays include vapor-filled electron tubes and are studied in Chaps. 10 and 11. In more advanced circuits (Chaps. 22 and 23) the phototube responds to changes of light or heat in the same manner as in circuits already studied; however, since these relays must respond to very short or rapid changes of light, their circuits must include special features yet to be studied.

The success of any photoelectric relay depends on the optical, or light, system used. Standard light-sensitive relays may solve most needs, when they are properly combined with lens, mirrors or light-filtering systems; that is beyond the electronic field of this book. The phototube may sort colored objects or respond to certain colors of light, as is discussed in Sec. 19-11.

Questions

1. Suppose that a photoelectric relay (as described in Sec. 8-3) fails to respond to a change of light; the *CR* relay will not drop out. Which of the following may be the trouble?

a. Heater of tube 2 is open-circuited.
b. Capacitor 1*C* is shorted.
c. Resistor 1*R* is open-circuited.
d. Resistor 7*R* is open-circuited.
e. Resistor 5*R* is open-circuited.
f. Coil of *CR* is shorted.
g. Resistor 6*R* is open-circuited.

Which diagram did you use, Fig. 8*B* or Fig. 8*C*?

2. In the Protectoglow circuit, Fig. 8*G*, which of the following will drop out *Z* and shut off the fuel?

a. The 45-volt transformer winding is open-circuited.
b. Resistor 4*R* is shorted.
c. Capacitor 1*C* is shorted.
d. Resistor 2*R* is open-circuited.
e. Tube-*A* heater is open-circuited.

3. In Fig. 8*H*, tube *A* causes a voltage that is (+) at 15, while tube *B* causes a voltage that is (−) at 16.

a. Because of these voltages, is 15 more positive than 16? Explain.
b. If tube *Y* is removed from its socket, does the indicator show a high-temperature reading?
c. If 4*R* is shorted, what happens?
d. If tube *A* is removed, what happens to the voltage across 6*R*? Across 4*R*?

4. In Fig. 8*E*, when does grid current flow in tube *T*?

CHAPTER 9

CONTROLLING LARGE CURRENTS WITH TUBES

In the circuits described this far, high-vacuum tubes have been used, most of which are like the tubes found in radio receivers. We have seen that such high-vacuum tubes carry small anode currents, generally from 1 to 100 milliamperes (or $\frac{1}{1000}$ to $\frac{1}{10}$ ampere). For industrial circuits, we often need tubes that carry large currents, from 1 to 100 amperes, even reaching 5000 amperes for an instant. Such high-current tubes are usually vapor filled; because they work differently, these tubes are often marked on diagrams by placing a dot inside the tube circle. Some of these gas- or vapor-filled tubes have heated cathodes and are called *phanotrons* or *thyratrons*, which are generally used to carry current in the range from $\frac{1}{10}$ to 40 amperes. Another type is called an *ignitron;* it contains a pool of mercury (unheated) as a cathode and is used to carry current greater than 40 amperes.

9-1. The Phanotron Rectifier.—The phanotron is a diode (a two-element tube, having only an anode and a cathode). When it is being made, a drop of mercury or some gas such as argon or helium is put inside before the tube is sealed. This tube behaves like the diode described in Secs. 2-4 to 2-6; as it has a heated cathode, electrons flow from cathode to anode whenever the anode is positive. Having no control grid, it is merely a rectifier tube. However, owing to the vapor or gas inside it, this tube may carry perhaps a hundred times as much current as a high-vacuum tube of the same size. When it is operating, this tube shows its red-hot filament; in addition, when anode current flows, a phanotron lights up with a colored glow, usually blue or purple. Some phanotrons have a metal enclosure, so that the glow is seen only where the anode connection passes through a glass seal.

The two-tube rectifier shown in Fig. 9*A* has two phanotrons connected like the tubes in Fig. 2*I*; it operates as a rectifier, to supply loads such as magnetic chucks or d-c motor fields. Since these vapor-filled tubes carry so much more current, their heated

cathodes must be able to produce more electrons. Therefore, the larger vapor-filled tubes are built with indirectly heated cathodes, as described in Sec 2-11 While ordinary radio tubes will reach operating temperature in 5 to 20 seconds, the vapor-

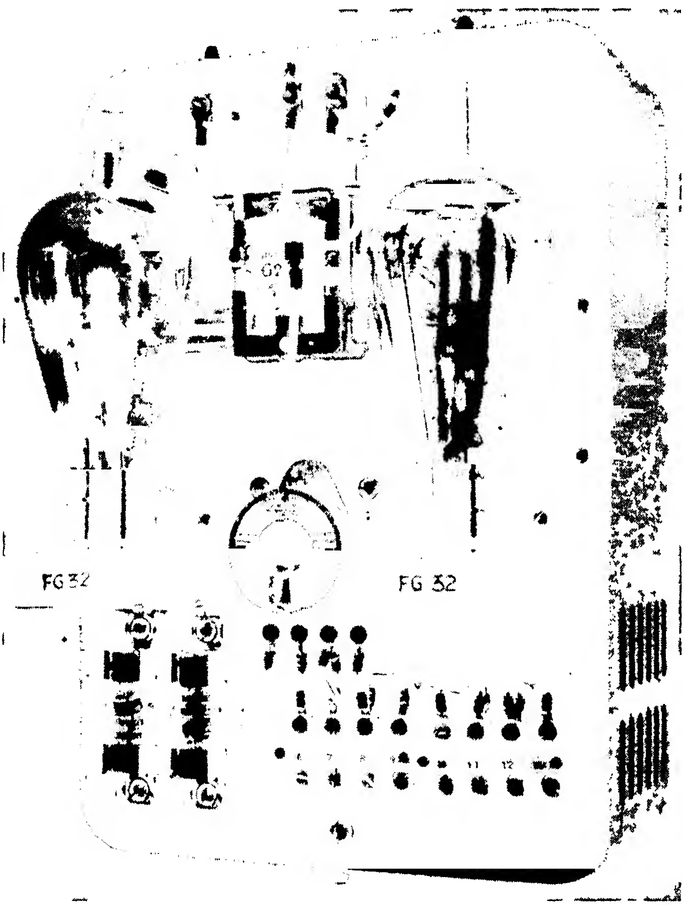


Fig 9A —A Phanotron rectifier (CR7501)

filled tubes may need a longer warming time; their life is greatly decreased if they are permitted to carry current before the cathodes have reached proper temperature The large industrial tubes must be protected by a time-delay relay (such as is included in Fig. 9A), which makes a contactor close a circuit between the load and the tubes

9-2. Greater Electron Flow in a Phanotron.—Why does the addition of vapor or gas permit a tube to carry so much greater current? Let us recall[7-1] that the flow of electrons through a tube generally does not use all the electrons that are being emitted from the hot cathode. In a high-vacuum tube, many extra electrons gather near the cathode, causing the space charge,[7-2] which tries to prevent other electrons from flowing to the anode. When there is vapor or gas inside the tube, some of the electrons bump into the small particles of gas with enough force to give these gas particles the power also to act like electrons and carry current. In these collisions, electrons give the gas particles this power by putting electric charges on them, or ionizing them. When the gas particles become charged in this way, we say that the gas is *ionized.* These collisions also produce a positive charge, which removes or offsets most of the space charge, so that the electrons are free to travel from the cathode to the anode. Nothing tries to limit the flow of electrons in the tube until this electron flow tries to become greater than the amount of electrons being emitted from the cathode. Since such operation quickly damages most cathodes, we must not let too much current flow through a vapor-filled tube. This current depends on the circuit outside the tube, just as the current through a switch or a contactor is limited only by the amount of load connected to the contacts.

9-3. Arc Drop—Constant Voltage across a Vapor-filled Tube. If you carefully measure* the voltage between anode and cathode of a high-vacuum tube, this voltage may be any amount, such as 5, 25, 90 or 350 volts; it changes when the amount of anode current changes. In contrast, when you measure from anode to cathode of a mercury-vapor-filled tube through which anode current is flowing, you read about 15 to 20 volts, and this voltage drop changes very little when the amount of anode current changes. Since the voltage drop across the current arc remains unchanged, we say that a gas-filled or vapor-filled tube has constant arc drop. For any phanotron, thyratron or ignitron containing mercury vapor, this arc drop is about 15 volts. If, say, 220 volts is applied across such a tube, together with its load, only 15 volts appears across the tube, 205 volts across the load.

* With the proper instrument, such as a vacuum-tube voltmeter.[27-1]

When current flow stops, the entire 220 volts is measured across the tube.

When a gas is used inside the tube in place of mercury vapor, the arc drop is also low if the tube has a heated cathode. However, with a cold cathode, a tube filled with neon may have about 75 volts' drop, while its anode current flows; other gases are used to make tubes having 90, 105 or 150 volts' drop, and these are the voltage-regulator tubes described in Sec. 10-6. All such tubes have constant arc drop—if the voltage across the tube is 75 volts when 10-ma anode current flows, you still measure 75 volts when the anode current increases to 30 ma.

9-4. Watching the Two-tube Rectifier Work.—Rectifiers somewhat like Fig. 9*A* may be used for d-c loads from 1 to 40 amperes.

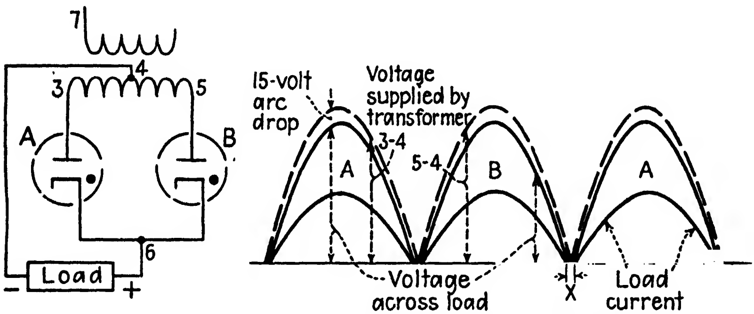


FIG. 9*B*.—Two-tube rectifier with resistance load.

When such a rectifier is supplying direct current to a resistance load (such as to heaters or certain d-c motor armatures) the curves in Fig. 9*B* show the voltage applied across the load and the resulting current flow. The dotted line (rectified sine wave) shows the voltage supplied by the transformer, first to the anode of tube *A* and then to the anode of tube *B*. Whenever this voltage is greater than 15 volts, current flows through the load and through one of the tubes. Notice that, since the voltage drop or loss across either tube is always 15 volts, the rest of the voltage is applied across the load, and its waveshape is nearly the same as the transformer voltage wave. For this resistance load, the current wave also has nearly the same shape as the voltage wave; there is no current flow during the short intervals marked *X*.

Usually the load includes some inductance or is highly induc-

tive, such as the winding of a magnetic chuck or the field winding of a d-c motor. The two-tube rectifier applies the same waveshape of voltage to such a load, as shown in Fig. 9C, but the resulting current flow has a different waveshape than with the previous resistance load. Just as a large flywheel turns very slowly at first, but gains speed while an engine continues to drive it, so the current flow through a large inductance increases very slowly; in Fig. 9C the current rises during one cycle after another, until the amount of current has reached a value limited by only the true resistance of the load. The current flow does not stop (as during *X* in Fig. 9*B*); instead, the load inductance produces a voltage (at *Y* in Fig. 9*C*) which forces the tube-*A* cathode more negative for an instant, so that tube *A* continues to

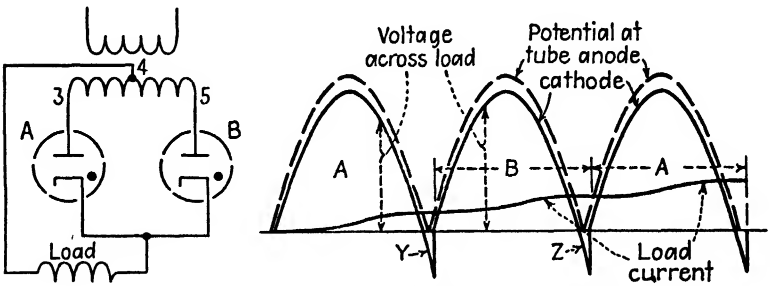


FIG. 9C.—Two-tube rectifier with inductive load.

pass current until tube *B* takes over the load. Similarly, at *Z* tube *B* is forced to continue to pass current until tube *A* again fires or conducts.

Just as a flywheel turns steadily, although driven by sudden pushes from an engine, so the current flows more steadily through this inductive kind of load, although this current is being produced by a rapidly changing voltage wave.

We shall study such two-tube rectifiers as part of the thyratron motor controls in Chap. 24. Similarly, three-tube and six-tube rectifiers are described in Chap. 18, for stored-energy welding. Larger power rectifiers must supply current greater than can be handled by hot-cathode tubes; for such rectifiers, and for the control of larger welders, we need another type of vapor-filled tube, called the ignitron, soon to be described.

9-5. Electron Tubes as an A-c Switch.—Although nearly every type of electron tube acts as a rectifier, a pair of tubes can

be connected, as in Fig. 9*D*, to pass alternating current and to act as a single-pole a-c switch. This connection, wherein the anode of each tube is connected to the cathode of its companion tube, is known as the "back-to-back," or inverse-parallel, connection. As shown in Fig. 9*D*, tube *A* passes current during the half cycle marked *A*; line 2 is positive during this half cycle, so electrons pass from line 1 through the load to point 3 and up through tube *A* to line 2. During those half cycles marked *B*, line 1 is positive, so electrons pass from line 2, up through tube *B* to point 3, and through the load to line 1. In each case electrons flow in just one tube, cathode to anode; current flows in *either* direction through this combination of tubes.

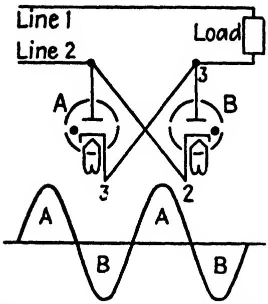


FIG. 9*D*.—Tubes connected back-to-back.

Unless these tubes have control grids, such a circuit serves no purpose, for the alternating current flows continuously, as if a copper strap were connecting points 2 and 3. If the tubes have grids, there is no current flow as long as the grids are kept sufficiently negative. When the grid potential of both tubes is raised, both tubes pass current, so alternating current flows through the load. In this way, two tubes act together like a single-pole a-c contactor, but have the advantages that they are noiseless and have no moving parts.

If these tubes happen to be high-vacuum tubes (pliotrons), their grids can control the amount of current flowing at any instant. However, since pliotrons necessarily have low-current ratings, they are little used for a-c switching.

Thyratrons (vapor-filled tubes with control grids) are commonly used to handle as much as 40 amperes per circuit. Since thyratrons are gaseous or vapor-filled tubes, we shall see (in Chap. 11) that their grids can prevent current flow, but they cannot control the amount of current flowing at any instant. Whenever the grid permits the thyratron to "fire" or pass current, the amount of that current is limited only by the external load circuit. This current continues to flow during the rest of the half cycle or until after the anode voltage reverses. For practical purposes, in an a-c circuit we may consider that vapor-filled tubes can be grid-controlled so as to either close or open the circuit,

9-6. The Ignitron.—To control large a-c loads, ignitron tubes are commonly used, connected in pairs like the thyratrons just discussed. The various sizes of ignitron that are available will handle currents from 40 to 10,000 amperes, per pair of tubes. Figure 9*E* shows two ignitrons connected to switch one side of an a-c circuit feeding the load of a transformer, such as found in a spot welder. Although ignitrons are sometimes used to handle steady or maintained loads of hundreds of amperes, their ability to carry extremely high currents for a short time makes them especially suited to the frequent switching of larger currents. It is common practice to use a pair of ignitrons to pass several thousand amperes for only one or two cycles, repeated on and off a hundred times per minute.

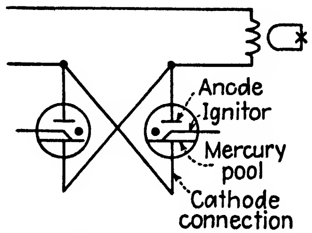


FIG. 9*E*.—Ignitrons, back-to-back, switching a welder load.

The ignitron is a gaseous* tube, but it is not a heated or thermionic tube. As shown by its symbol in Fig. 9*E*, it has no filament, but uses a pool of liquid mercury as its cathode (like most mercury-arc rectifiers), so the enclosure contains mercury vapor. If an arc can be started by some means within the ignitron, huge quantities of electrons are driven up out of the surface of the mercury pool and are attracted to the single large carbon anode whenever that anode is much more positive than the mercury pool. Notice that the ignitron, like most electron tubes, is a rectifier—it produces electrons from only one element, the mercury pool, so its electrons can flow in only one direction, from cathode to anode. So much current may flow in such a tube that a large amount of heat is produced during normal operation. This heat must be removed from the tube; enough water must circulate in the tube water jacket to keep the tube within its safe operating temperature limit. In most circuits the contacts of a thermal flow switch will prevent the flow of current through the ignitrons if the water temperature becomes too high. The metal water jacket and tube wall are electrically connected

* If air leaks into a vapor-filled or gaseous tube, it becomes a "gassy" tube or "leaker," and will not operate correctly. A gassy tube passes anode current whenever its anode is positive, regardless of its grid or ignitor.

to the mercury-pool cathode, as shown in the cutaway view in Fig. 9*F*.

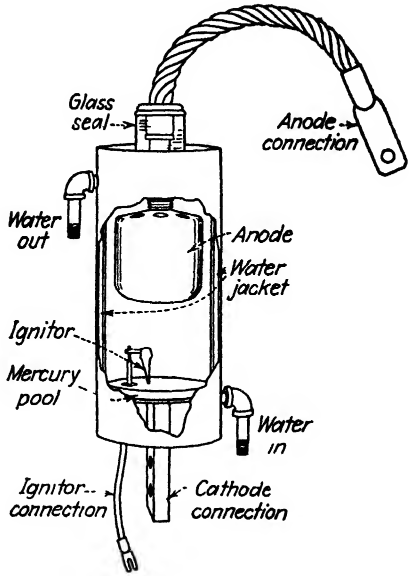


FIG. 9*F*.—Ignition tube cut away to show inside.

9-7. The Ignitor.—Unless we furnish some means for starting an arc inside the ignitron, current cannot flow, for no electrons are freed from the cathode. In contrast, a thyratron passes current whenever the anode is more positive than the cathode and there is no restraining grid potential present. With nothing connected to its grid, a thyratron may pass anode current; without an ignitor or means of starting an arc, an ignitron cannot fire.

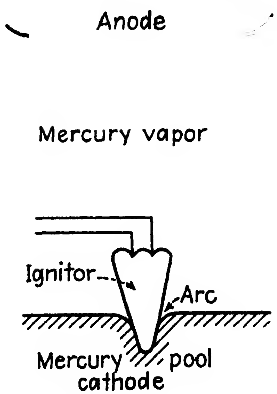


FIG. 9*G*.—Parts that fire an ignition.

The ignitor, or starter, is a tapered piece of boron carbide that extends down into the mercury pool but is not wet by it. As shown in Fig. 9*G*, the mercury surface is slightly depressed by the ignitor tip. The material of the ignitor is selected because there is considerable resistance (10 to 500 ohms) measured

between the ignitor and the mercury pool while they are in direct contact. This being true, it is possible to cause a tiny arc* between the tip and the pool, if enough electrons (40 amperes) are made to flow from the mercury into the ignitor. This 40 amperes needs to flow only for a few millionths of a second, as the tiny arc spreads between the cathode pool and the anode, and ionizes[9-2] the particles of mercury vapor in the space between. Enough energy is obtained from the arc itself to free other electrons from the pool to carry any required current, which continues to flow until after the anode voltage is reversed at the end of that half cycle. Of course, this whole process must be repeated for each half cycle during which the ignitron is to pass current. When anode current has started, the ignitor arc is no longer needed; we shall soon see that the ignitor current stops as anode current starts.

9-8. Simple Ignitron Control.—The simplest possible arrangement for controlling ignitrons is shown in Fig. 9*H*. If you close switches *S* and *T* at the point marked *X* (in half cycle *A*, during which line 2 is positive), ignitron *A* instantly passes current, which flows during the rest of half cycle *A*. However, ignitron *B* cannot pass current until half cycle *B* (when line 1 is positive) and after the current of tube *A* stops.

Notice that the circuit through *S* and the ignitor is in parallel with the main cathode-to-anode circuit of tube *A*. When *S* closes, current first flows through the ignitor and *S*, causing the arc that ionizes the mercury vapor in tube *A*. This instantly permits load electrons to flow directly from cathode to anode in tube *A*. The resistance of this main current path from cathode to anode is so much lower than that of the circuit through the

* Although only a 150-volt drop is needed for starting this arc, this voltage is applied between parts that are so close together that an extremely high voltage gradient exists, producing an intense electric field, which pulls electrons out of the mercury pool. This is the fourth form of electron emission that we have encountered:

1. Thermionic emission, occurring when the cathode is heated.[2-6,7-1]
2. Photoelectric emission, occurring when certain cathode materials receive light energy.[3-8]
3. Secondary emission, occurring when the anode or grid is hit by other electrons.[7-8]
4. Field emission, occurring when a very great electric field is present (see above).
5. Radioactive emission, given off from materials like radium.[19-12]

ignitor resistance and *S* that the current flowing in the ignitor becomes very small. As soon as the current stops flowing in tube *A* and the potential at the anode of ignitron *B* has become more positive than its cathode, tube *B* is then "fired" in the same manner, by electrons flowing first through the ignitor and switch *T*, which instantly makes the mercury vapor in tube *B* able to carry the load electrons directly from cathode to anode. We see that, although the load current is carried mainly by the cathode-anode circuit, this flow must be started, or "ignited," every half cycle separately. In Chap. 13 we will see how switches *S* and *T* are replaced by thyratron tubes, to control the current flow through the ignitors and provide more accurate starting of ignitron tubes.

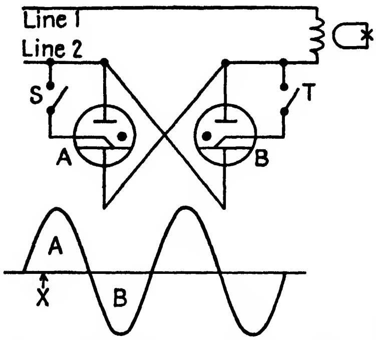


FIG. 9*H*.—Simple method (never used) for firing ignitrons.

9-9. The Ignitor-firing Circuit.—Instead of two ignitor circuits controlled by separate switches (as in Fig. 9*H*), the ignitors can be connected together through a single control contact *C*, as shown in Fig. 9*I*. With *C* closed and line 2 positive, electrons flow from line 1, through the load to point 3, from the mercury pool of tube *A* into its ignitor to 5, through contact *C* and into ignitor 4, to the mercury pool of tube *B*, to point 2 and line 2. This causes the arc between cathode 3 and ignitor 5, and "fires" tube *A*, which immediately passes electrons from cathode 3 to anode 2. Although this ignitor current fires tube *A* in normal fashion, these same electrons flow in reverse direction in tube *B*, or from ignitor to pool. Such reverse current definitely damages the ignitor and decreases tube life. To prevent this reverse current, copper-oxide (metallic) rectifiers[28-13] are added, as shown in Fig. 9*J*. Each rectifier is a stack of copper disks, arranged so that they have very high resistance to electron flow

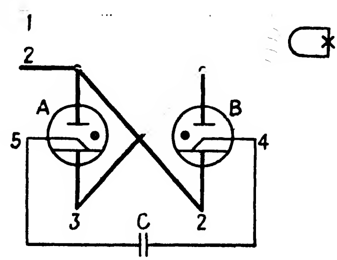


FIG. 9*I*.—One contact *C* may fire both ignitrons.

in the direction indicated by the symbol arrow, but they have low resistance to opposite electron flow.

9-10. Ignitron Contactor.—Figure 9*J* shows the circuit used in a typical ignitron contactor. The ignitrons, connected back to back, close or open only one side of the a-c line. Both ignitrons pass current when the control switch is closed. To fire ignitron tube 1, electrons first flow *ABCDEFGHIJ*. This current, flowing through ignitor *D*, causes tube 1 to pass electrons which flow *ABCJ*. During the following half cycle, ignitor electrons flow first through path *JIKHGFECBA*, which fires tube 2 so that load electrons then flow *JIBA*.

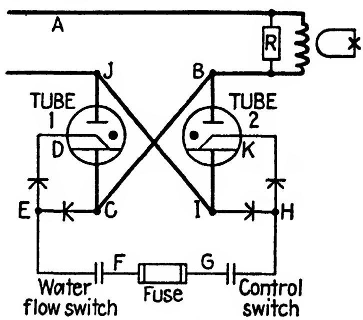


FIG. 9*J*.—Circuit of ignitron contactor.

The control circuit *EFGH* carries each ignitor's current in turn. Although this current must reach 25 to 40 amperes momentarily to fire the ignitron, it flows such a small portion of each cycle that a 3- or 6-ampere fuse serves during normal operation. If an ignitron fails to fire or becomes "hard starting," the ignitor current flows a larger portion of each cycle, and blows the fuse. In the same circuit, the flow-switch contact opens when there is not enough water flowing to cool the ignitrons.

In Fig. 9*J*, notice resistor *R* connected across the welding transformer. This resistor is furnished with the ignitron contactor and is usually a Thyrite[28-12] unit, to by-pass surge voltages. In a circuit using ignitrons or thyratrons, it is desirable to use such Thyrite resistors across any inductive load, such as a transformer or a motor field; to be effective, the Thyrite must be connected close to the inductive load.

9-11. Oscilloscope Pictures of Circuit Operation.—Although the ignitron contactor just described is widely used, this same arrangement of ignitron tubes is also a basic part of more complex controls for resistance welders, as described in Chap. 12. In service, the performance of such ignitron tubes and thyratrons is best observed by means of an oscilloscope.[27-5] The odd waveshapes seen with the "scope" connected in a typical welder circuit, are shown in Fig. 9*L*. To understand these better, we

must remember the constant arc drop[9-3] of a vapor-filled tube, and then see how the power factor of the load affects the tube operation.

From experience we know that when a switch controls a load, the entire circuit voltage appears across the open contacts of the switch. When the switch closes, no voltage remains across the contacts but the circuit voltage appears across the load. Similarly, ignitrons have circuit voltage between anode and cathode as long as no current flows. When these tubes "fire," the circuit voltage disappears from across the tubes and appears across the load—that is, all except about 15 volts. A drop of 15 to 20 volts remains across the tube when it passes current; this is the arc

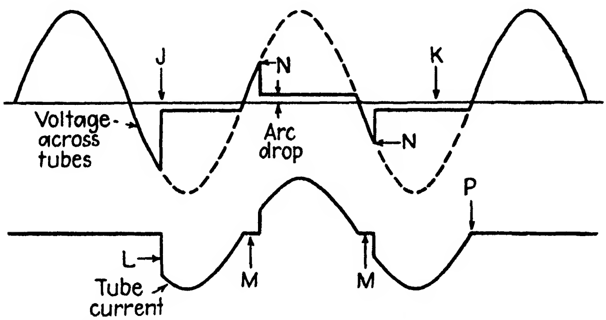


FIG. 9K Waveshapes of voltage and current ignitrons with resistance load

drop of a mercury-vapor-filled tube, described above.[9-3] The amount of tube current causes little change in this arc drop.

If oscilloscope leads are connected to anode and cathode of such a tube, the trace of a-c line voltage is seen until the tube fires When tube current flows, the trace drops instantly to within 15 volts of the zero center line. Figure 9*K* shows such a voltage trace measured across the tubes in an ignitron contactor. The control switch closes at *J* and opens at *K*. Here we assume a resistance load (noninductive), so the current is shown in phase with the voltage. Notice the current at *L*, rising suddenly to its normal value on the sine wave. Notice also that no current flows at *M*, because an ignitron cannot pass current until the voltage wave rises high enough (at *N*) to force enough ignitor current to cause the arc at the ignitor tip. At least 150 volts may be required before the ignitron fires. Notice also that, although the

control switch opens at *K*, the tube does not stop its current flow until *P*, where its anode voltage reverses.

9-12. Operation with Welder Load.—For comparison with Fig. 9*K*, the curves in Fig. 9*L* show how the ignitron contactor behaves when it passes current to a welder transformer, which is a lagging-power-factor load and is highly inductive. When current flows, it lags behind the voltage by the amount *R*. When the control switch closes at *Q*, the current does not increase suddenly at *S*,

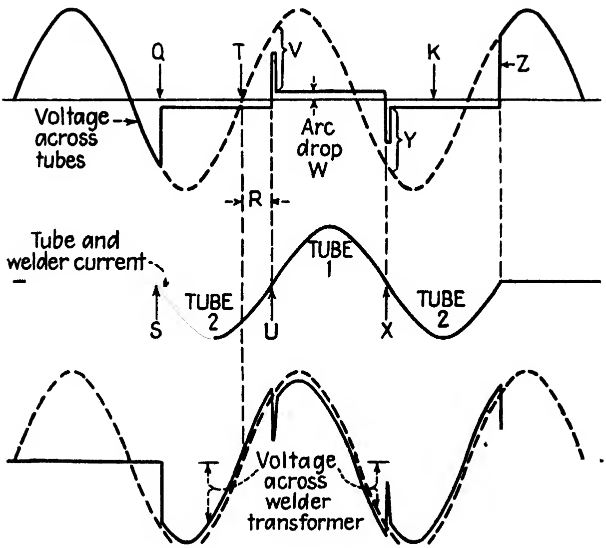


FIG. 9*L*.—Waveshapes of ignitron contactor with welder load.

for the welder inductance (acting like a flywheel) prevents any sudden current change. Instead, the current increases gradually, like a sine wave. As soon as this current starts, the voltage across the tubes immediately decreases to the 15-volt arc drop. Notice that, although the circuit voltage reverses at *T*, tube 2 does not stop nor does tube 1 start at this point. Instead, tube 2 continues to pass current later than *T*, for the energy stored in the inductance of the welder transformer forces this current to flow until *U*.

Meanwhile, as long as tube 2 continues to pass current, the anode-to-cathode voltage of both tubes is only 15 volts, which is not enough to fire tube 1. When the tube-2 current stops at *U* (since no energy remains in the welder transformer to cause

further current flow), suddenly the entire voltage V becomes available across tube 1. This voltage V quickly forces current through tube-1 ignitor and fires tube 1. This all occurs within a few microseconds—so fast that the voltage trace on the oscilloscope does not have time to reach the line voltage curve at V but returns to the arc-drop voltage at W. Tube 1 now carries all the current until, at point X, the current dies out and voltage Y is then able to restart tube 2. At K, the control switch is opened, but tube 2 continues to pass current until the end of its half cycle. As this current stops, voltage Z appears across tube 1, but it cannot restart tube 1, for the ignitor circuit is now open.

During every instant that tube current flows, voltage is applied to the welder transformer. If the oscilloscope leads are connected across the welder-transformer primary, a trace appears similar to the lower curve in Fig. 9L.

9-13. Ratings of Vapor-filled Tubes.—Since an ignitron contactor consists mainly of a pair of big tubes, we naturally must be

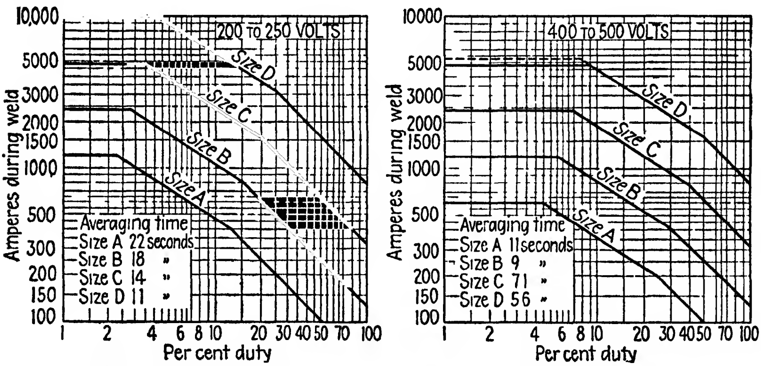


FIG. 9M.—Rating curves of ignitron tubes (a pair) at 230 and 460 volts.

concerned with the methods of rating and selecting these tubes. Although the final answer depends on the use of curves* in Fig. 9M, several vital points should be emphasized here.

For use with resistance welders, the four standard sizes of ignitrons (also known as size A, size B, size C and size D) can carry continuous loads of 50, 120, 300 and 800 amperes per pair of tubes, at voltages between 200 and 500. However, at 50 per

* For more complete discussion of ignitrons and their selection for various load conditions, refer to Chap. 5 of "Electronic Control of Resistance Welding," McGraw-Hill Book Company, Inc., New York, 1943.

cent duty, these ratings become twice as great. In contrast, the rating of a motor or transformer operating at 50 per cent duty increases only 41 per cent, because the heating increases as the square of the load current. To explain why the ignitron rating doubles, recall that the arc drop[9-3] of a gaseous tube carrying little current is the same number of volts as when it is carrying full or overload current. Since arc-drop voltage E is constant, and $E = IR$ (or voltage equals current multiplied by resistance), then the internal resistance of the tube must be decreasing as the current increases. In this way a vapor-filled tube does not behave like ordinary current conductors, but the heating of the tube increases only in direct proportion to the load current. As a result, all vapor-filled tubes are rated in average amperes instead of amperes rms. At duty cycles below 50 per cent, heating is not the only limiting factor, as is shown by the left-hand portion of Fig. 9*M*.

9-14. Averaging Time.—Speaking of a motor operating at 50 per cent duty, we think in terms of overloading the motor for perhaps 30 min during each hour. Experience warns us not to overload the motor for one day continuously, followed by one day of rest, even though this is still 50 per cent duty. We know this 50 per cent applies to a reasonable time, such as 1 or 2 hours, which is the "averaging time" during which the motor can safely store up excess heat with the hope of radiating it during the following periods of light load. All electron tubes likewise have a value of averaging time, and it is very short—a matter of merely seconds, not minutes or hours. Electron tubes have no mass of metal comparable to a motor of equal current rating, so a tube reaches damaging temperatures in less than a minute of overload operation. Ignitrons selected for 50 per cent duty may carry their larger current for 1 out of 2 sec, but not for 1 out of 2 min, for this exceeds the published averaging time of the tube. Electron tubes may "do wonders," but they still have load ratings or limits like other electric equipment.

The ignitron contactor is used mostly as a welding control; it can be used in other a-c circuits, where currents must be quickly started or broken. The ignitron contactor also permits the gradual control of the amount of alternating current supplied to a load, if the ignitrons are controlled by "phase-shifted" thyratrons, as described in Chap. 13.

Questions

1. In Fig. 9*B*, if an a-c voltmeter reads 600 volts between 3 and 5, what does it read between (*a*) 3 and 6? (*b*) 3 and 7? (*c*) 5 and 7? (*d*) 4 and 5? (*e*) 4 and 6?

2. In Fig. 9*J*, if a good voltmeter is connected between the following points, while the control switch is open, does the voltmeter read zero, full line voltage or part voltage (because of the drop in tubes, rectifiers, welder or fuse)?

a. Voltmeter between *G* and *H*.
b. Between metal shell of tube *A* and metal shell of tube *B*
c. Between *J* and *B*.
d. Between *G* and *A*.
e. Between *D* and *K*.

3. If the fuse in Fig. 9*J* blows, which may be the trouble?

a. The control switch is closed too long.
b. A rectifier is shorted, between *D* and *E*.
c. An ignitron is hard starting.
d. A rectifier is shorted, between *H* and *I*.
e. An ignitron is gassy.

True or false? Explain why.

4. Current in a capacitor can change instantly.

5. Voltage across an inductance or reactor can change instantly

6. Voltage across a capacitor can change instantly.

7. An ignitron will fire if its ignitor becomes positive.

8. A two-tube, full-wave rectifier (without filter) furnishes a smooth flow of direct current to a resistance load.

9. Four ignitrons would be needed to close both sides of an a-c circuit, like a two-pole contactor.

10. When two ignitrons are connected in parallel, or two thyratrons are connected back to back, only one tube passes current at any instant.

CHAPTER 10

OBTAINING D-C POWER SUPPLY FOR TUBE CIRCUITS

Most electronic equipments operate from alternating-current supply, for convenience. Within these equipments, most of the tube circuits use direct current (or d-c voltage) to give best results. Therefore, the first part of a complete electronic circuit (whether it be a radio, a synchronous welding control, an oscilloscope or a high-speed photoelectric relay) is quite likely to be a rectifier tube combined with other devices, whose only purpose is to convert part of the a-c power into a d-c supply suitable for other tube circuits. When an electronic equipment must give more accurate response and be sensitive to very tiny changes of control signal, the built-in d-c supply voltages must be carefully protected from changes caused by disturbances other than the signal itself. As an example of an electronic equipment that uses many such circuit refinements, we examine a photoelectric pyrometer.

10-1. Photoelectric Pyrometer.—This equipment responds to the heat or temperature of white-hot metal or other material, so as to close an alarm circuit if the material becomes too hot. Instead of using a thermometer or a thermocouple[28-14] exposed to the heat, this pyrometer uses a phototube (quite like the one in Sec. 3-8 or 8-7), which "looks at" the hot metal. When the metal is cool, very little current flows through the phototube; as the temperature increases, the current through the phototube increases. At high temperatures, a change of only 5 or 10 degrees produces a change in phototube current; however, this current change is so small that its effect is lost unless the entire circuit is kept at steady voltages throughout.

The complete circuit of such a photoelectric pyrometer is shown in Fig. 10*A*, where phototube 4 is receiving the radiation from the hot metal. As would be expected, this circuit appears at first to be quite complex and difficult to understand. We hope to

show that its basic circuit is simple, but that many parts have been added so as to give a very good d-c power supply and to "brace" the circuit against unwanted signals. This is like a precision gauge, set up to detect or measure a movement of 0.0002 or $\frac{1}{5000}$ inch; if the floor or the table under the gauge vibrates or moves $\frac{1}{1000}$ inch, how can you hope to detect a movement smaller than this unwanted disturbance?

10-2. Basic Circuit Operation.—Robbed of all its protective refinements, this pyrometer circuit is shown in Fig. 10*B*. The rectangle at the left contains the d-c power supply, which furnishes steady voltage between points 4 (top) and 2 (bottom). Phototube 4 and resistor 7*R* are connected across this steady

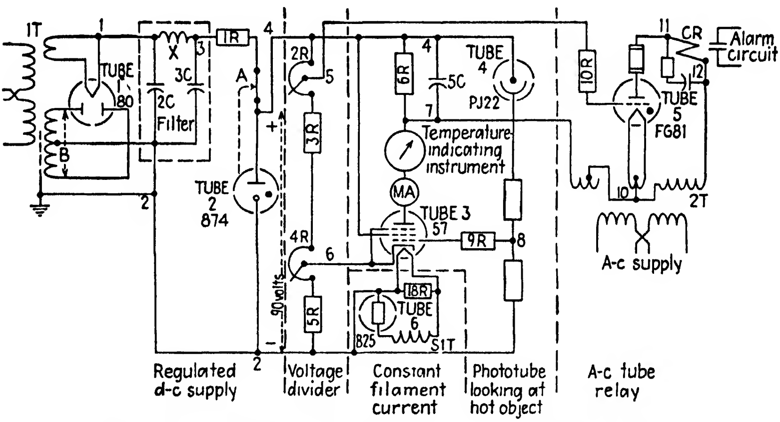


FIG. 10*A*.—Circuit of photoelectric pyrometer (CR7505R).

voltage and act as a voltage divider, whose middle connection 8 is at the control grid of tube 3. When phototube 4 "looks at" cool metal, so little current flows through the phototube and 7*R* that the potential at grid 8 is nearly as low as point 2; by adjustment of the slider of 4*R*, the cathode potential of tube 3 is made much higher than grid 8, so that tube 3 passes no current. Therefore, no current flows through the milliammeter *MA* or resistor 6*R*; with no voltage drop across 6*R*, point 7 is at the high (positive) potential of point 4. By moving downward the slider of 2*R*, the grid of tube 5 is made more negative than point 7 (cathode), until tube 5 does not fire or pass current; relay *CR* is not picked up, or energized.

When hotter metal causes phototube 4 to pass more current,

which must also flow through $7R$, then the grid potential at 8 rises and turns on or increases the current flow of tube 3. These electrons flow from negative point 2, through $4R$ to point 6, from cathode to anode of tube 3, and through MA and $6R$ to positive point 4. This current causes a voltage drop across $6R$, so that the potential at point 7 decreases, lowering the cathode of tube 5 until its grid (held constant at point 5 on $2R$) is able to "fire" tube 5. Notice that the anode voltage of tube 5 is supplied by transformer $2T$, so that tube 5 operates on alternating current, although its grid voltage is obtained from the d-c system (between points 5 and 7). Tube 5 is a thyratron (vapor-filled tube with

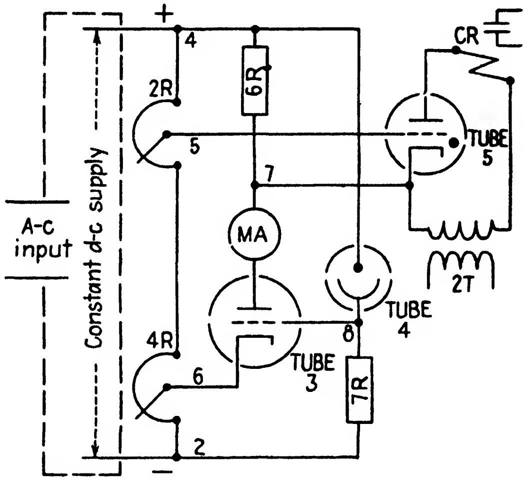


FIG. 10B.—Simplified pyrometer circuit.

grid control); in Chap. 11 we shall see why it needs a separate a-c supply. For the present, we point out that the anode current through tube 5 increases *suddenly,* picking up relay CR when the voltage between cathode 7 and grid 5 has decreased to just the right amount to "fire" tube 5.

Using an optical pyrometer to show the actual temperatures in degrees, you set $2R$ and $4R$ so that tube 5 does not fire while the metal is just hot enough;* when it gets too hot, the slightly increased light reaching phototube 4 causes tube 5 to fire, picking up CR to close the alarm or correction circuit.

* The indicating meter is marked to show the temperatures corresponding to different amounts of current through tube 3. Meter MA helps in adjusting $4R$.

10-3. Complete Pyrometer Circuit.—Returning to Fig. 10*A*, the left-hand side shows that the d-c supply is provided by rectifier tube 1 and its filter; such filter circuits, which remove the a-c ripple or "hum," are explained below. The resulting d-c voltage, between points 3 and 2, still may be disturbed by changes in a-c supply voltage, so we add voltage-regulator tube 2 and its buffer resistor 1*R*, to produce more constant voltage between points 4 and 2, as explained in Sec. 10-6. By addition of 3*R* and 5*R* in the voltage divider, the voltages at sliders 5 and 6 are held within desirable limits, so that 2*R* and 4*R* provide easy adjustment.

Notice that tube 3 in Fig. 10*A* is a pentode,[7-9] whose screen is connected to positive point 4, and its suppressor is connected to the cathode; this type of tube gives an output (or amount of current flowing through 6*R*) that is not affected by changes of anode voltage at point 7. To prevent any change in a-c filament current that might disturb the anode current of tube 3, notice the ballast tube 6, which holds constant current in its own circuit. As will be explained in Sec. 28-15, this ballast tube is not electronic.

Capacitor 5*C* steadies the voltage across 6*R* and prevents tube 5 from being fired by any momentary increase in tube-3 current. Near tube 5, resistor 10*R* limits the amount of grid current; the 2*T* secondary winding (between points 7 and 10) is mentioned later.[11-7]

Having seen how this pyrometer circuit is improved by these added features, now let us study the d-c power supply with its filter and regulator.

10-4. Filtering.—The circuit producing this direct current is shown again in Fig. 10*C*. Here we find a rectifier tube (previously met in Sec. 2-10) and its center-tapped anode transformer, which converts alternating voltage into a pulsating d-c voltage. Lower in Fig. 10*C*, we see that the output voltage (without filter) consists of half cycles, all above the 0 line; it is no longer a.c. but neither is it d.c. It produces pulsating current, which can be used for some d-c purposes but is not suitable for most tube circuits; it must be filtered to take out the unwanted ripple, or curve, that remains of the a-c waveshape. Just as a country gravel road becomes a rough "washboard" surface, which makes an automobile vibrate, so the ripples in this pulsating current can shake or disturb a tube circuit. Also, just as the

rough road is made smooth by scraping the ridge tops down into the grooves, or hollows, so this pulsating current is smoothed by electrical devices that take energy from the high spots and discharge or lay this energy into the low spots of the pulsating wave. As is shown in Fig. 10*C*, this smoothing of the voltage or current is done by making the tube-1 current pass through a reactor *X*, and by connecting capacitors 2*C* and 3*C* from *X* to the other (negative) side of the load. This combination* is called a *pi*

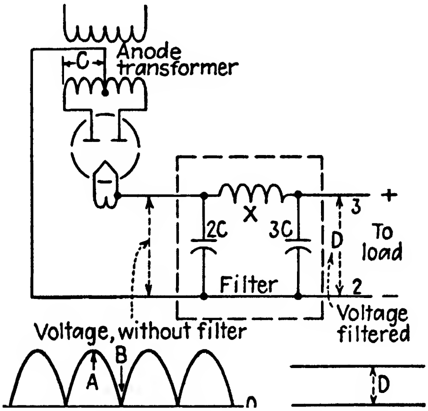


FIG. 10*C*.—D-c power supply—rectifier with pi filter.

filter, because the parts are arranged on the diagram so as to resemble the Greek letter pi (π).

This reactor *X* is made of wire, wound on an iron core, so that *X* has a large amount of inductance. This inductance tries to maintain a steady current through its winding, by storing energy during moments when current increases and then discharging this energy to help a decreasing current. So *X* helps to smooth the current wave by reducing the high spots and filling the low spots.

Similarly, capacitors 2*C* and 3*C* help to smooth the voltage across the load by charging or storing energy during the high-voltage parts of the wave (such as *A* in Fig. 10*C*) and then discharging this energy into *X* or into the load, during the low-voltage periods such as *B*.

The operation of a full-wave† rectifier with its filter circuit is

* Sometimes a resistor is used in place of *X*.

† Although classed as a biphase half-wave rectifier, this tube passes current during both halves of an a-c voltage wave.

like that of a two-cylinder water pump, equipped with surge tanks and a heavy paddle wheel, as shown in Fig. 10*D*. In each cylinder, the piston forces water into the pipe during its forward stroke. Just at the time when the pistons change direction, there is no force. The result is a pulsating water pressure, which is smoothed by the surge tanks and the paddle wheel. While one piston is in the middle of its forward stroke, its force starts the paddle wheel turning and also pumps water into tank *A*. Although at the end of the stroke there is no force from the pump, the heavy paddle wheel still tries to turn at the same speed and pass the same amount of water between its vanes. This water is supplied from tank *A*, and this lowers the water level there until the pump can again force water into the pipe and restore the water level in *A*. It is natural for the heavy paddle wheel to try to turn at constant speed and pass steady water flow, just as it is natural for an inductance or reactor *X* to try to pass steady flow of current. The water leaving the paddle wheel may still have small pressure changes, and these are further removed by the smoothing action of tank *B*, which receives water during any instant of higher pressure and discharges the water into the line at any instant of lower pressure.

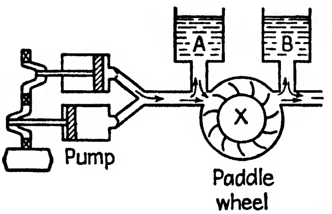


FIG. 10*D*.—Water system, acting like rectifier and filter of Fig. 10*C*.

10-5. Voltage Output from a Filter.—The d-c voltage output from a filter depends on the a-c voltage supplied to the rectifier tube anodes; the filter arrangement and the amount of d-c load also will change this output voltage. As a rough figure, a d-c voltmeter across the load (at *D* in Fig. 10*C*) reads about the same number of volts as an a-c voltmeter connected at *C* (across one-half of the anode transformer). This is also shown by the upper curve in Fig. 10*G*; at an output current of 75 to 100 ma, the output voltage from this pi filter is about 300 volts d.c., whereas the a-c voltage (at *C* in Fig. 10*C*) is 300 volts rms (as read by the usual a-c voltmeter). Notice that, as the d-c load decreases, the filter output voltage *D* rises toward 425 volts, which is the crest[5-6] value of the voltage applied at *C*.

To make clear why the filter-output voltage (*D* in Fig. 10*C*)

rises as the load decreases, the solid upper curve in Fig. 10*E* shows how the voltage changes across capacitor 2*C* while the d-c load is 100 ma; when this load is almost zero, Fig. 10*F* shows the result. In both diagrams we see that capacitor 2*C* is charged to the 425-volt crest value of the a-c wave. At point *K* this a-c wave decreases faster than capacitor 2*C* can discharge, so current

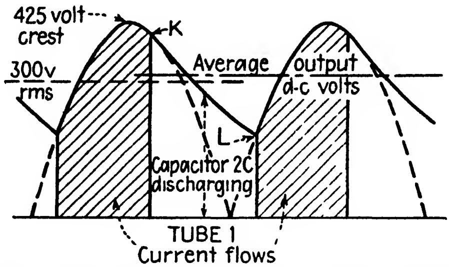


FIG. 10*E*.—Waveshapes of rectifier and filter at heavy load

through tube 1 stops; 2*C* continues to supply all the current needed by the load, until the other tube anode passes current, at *L*. When supplying a d-c load of 100 ma, the capacitor 2*C* loses its voltage quickly, decreasing to *L* in Fig. 10*E*. As a result, the average height of the voltage across 2*C* is much lower than the crest voltage. The corresponding output voltage of the filter, after being smoothed by *X* and 3*C*, is slightly below this average

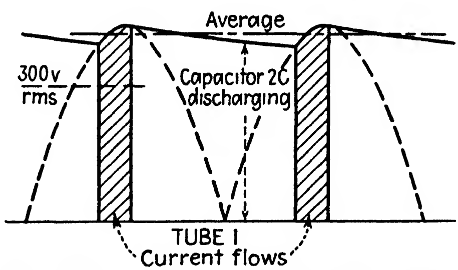


FIG. 10*F*.—Waveshapes of rectifier and filter at light load.

voltage in Fig. 10*E*. In contrast, when there is very little d-c load, capacitor 2*C* does not need to give up much of its charge or lose its voltage. Figure 10*F* shows that the voltage across 2*C* remains very close to the crest of the a-c voltage wave, so that the average voltage of 2*C* is also high; the filter output is nearly the same as the 425-volt crest input.

The shaded portions in Figs. 10*E* and 10*F* show that tube 1 passes current in spurts, or during only part of each cycle. This is satisfactory for low-current d-c supplies, using high-vacuum rectifier tubes. When a vapor-filled rectifier tube is used with a

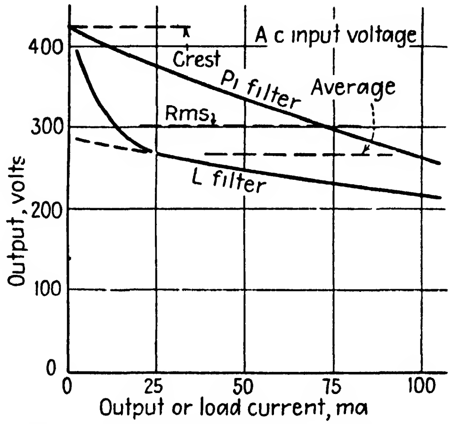


FIG. 10*G*. Filter voltage output as the load changes.

filter to supply a larger amount of direct current, the high momentary currents needed for charging capacitor 2*C* may be prevented if 2*C* is omitted, as next described.

When only reactor *X* and capacitor 3*C* are used, as shown in Fig. 10*H*, this arrangement is called an *L* filter. Here the current flowing in *X* flows also in tube 1 at the same instant. Since it is natural for inductance *X* to keep current flowing quite steadily through its own winding, this action also keeps current flowing continuously through tube 1. Moreover, as long as there is considerable load current, the crests of the a-c voltage wave do not reach capacitor 3*C*; instead, the output voltage of this *L* filter is close to the average value of the a-c supply wave, as shown in Fig. 10*G*.* However, if the d-c load current becomes small,

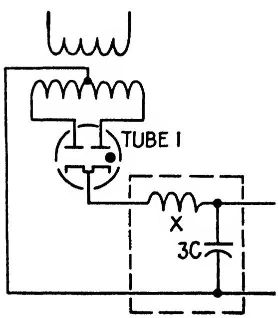


FIG. 10*H*. Rectifier with *L* filter.

* EASTMAN, A. V., "Fundamentals of Vacuum Tubes," 2d ed., p. 198, McGraw-Hill Book Company, Inc., New York, 1941.

reactor X loses its ability to smooth the voltage wave; the crest of the a-c wave then reaches $3C$, (as though X were not in the circuit) and the load voltage rises sharply toward the 425-volt point. In practice, the L filter is kept loaded and gives less variation of output voltage than the pi filter.

Some kinds of load act also as filters, since such loads contain enough inductance or capacity to smooth the current flow. This action is described in Sec. 9-4, where a highly inductive motor-field winding takes time to build up the flow of field current (in Fig. 9C) and then continues to draw a steady flow of current through the rectifier tubes.

10-6. The Voltage-regulator Tube.—After alternating current has been rectified and filtered, producing a smooth d-c voltage supply (as between points 3 and 2 in Fig. 10A), the amount of this voltage still may change, owing to dips or variations in a-c supply voltage, or owing to changes in the d-c load passing through the filter. By adding tube 2 and resistor $1R$, as shown again in Fig. 10I, we obtain a steady d-c voltage between points 4 and 2. Although the input voltage E may change from 130 to 150 volts, the output voltage EE remains at 90 volts; the "slack," or difference, appears across resistor $1R$, changing from 40 to 60 volts in this example. In this photoelectric pyrometer circuit (Fig. 10A) tube 2 is a type-874 voltage-regulator tube. Because of its electrode construction and the argon gas that fills its envelope at low pressure, this cold-cathode tube has a natural drop of 90 volts between anode and cathode; to do this, a current of 10 to 50 ma must flow through the tube at all times. Let us watch it work.

For a moment, in Fig. 10I, let us disconnect the load resistor LR, so that only tube 2 is in circuit with resistor $1R$. If input E is 130 volts, this entire voltage is applied across tube 2 until current starts to flow. The natural action of tube 2 is to pass enough current so that only 90 volts will remain between its anode and its cathode; this current, flowing also through the 1000 ohms of $1R$, must be of the right amount to absorb the difference between 130 volts and 90 volts, or 40 volts. By E/R, or dividing 40 volts by 1000 ohms, we find that 0.04 amp or 40 ma must flow through resistor $1R$ (and tube 2), so that only 90 volts remain across tube 2. If voltage E rises to 140 volts, tube 2 instantly responds by increasing its current flow to 50 ma; this greater current, flowing

through $1R$, increases the voltage across $1R$ to 50 volts; the voltage across tube 1 remains at 90 volts, while the 10-volt increase is absorbed across $1R$.

If we now reconnect or add the resistor LR (in Fig. 10*I*), which represents any voltage-divider or tube load connected to the regulated 90-volt d-c supply, notice how regulator tube 2 responds. If E is 130 volts, and LR totals 4500 ohms, the drop across $1R$ is still 40 volts, and the current through $1R$ is still 40 ma. However, part of this current now flows through LR, equal to 90 volts/4500 ohms equals 20 ma. When we add this 20-ma load drawn by LR, the current through $1R$ tries to increase and cause greater drop across $1R$, to decrease voltage EE. But tube 2 immediately decreases its own current, now drawing only 20 ma, so that the total current through tube 2 and LR is again 40 ma; EE remains at 90 volts.

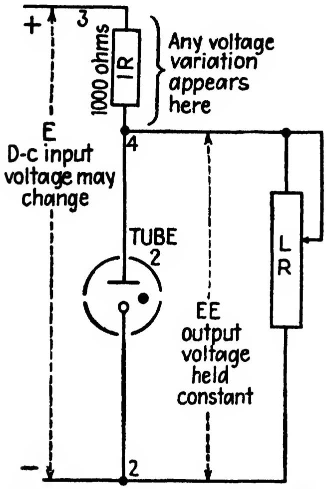


FIG. 10*I*.—Circuit of a voltage-regulator tube.

Similar to this 90-volt tube (type 874) there are voltage-regulator tubes containing other kinds of gas or different electrode shapes, which naturally hold other constant voltages; the 75-30, the 105-30 and 150-30 tubes hold about 75, 105 or 150 volts, when 5- to 30-ma current flows through them. About 35 volts greater than the working voltage must be used to start any tube. Here recall that a mercury-vapor-filled thyratron acts also as a voltage-regulator tube; with a heated or pool cathode, it holds only about 15 volts from its anode to its cathode.[9-3]

Two or more voltage-regulator tubes may be used in series, supplied from one higher voltage d-c source, and using one buffer resistor (see Fig. 24*D*). A regulator tube appears in some industrial circuits, not as part of the d-c supply, but merely to limit or to hold constant the voltage between two points in the circuit (see Fig. 17*I*).

10-7. Cold-cathode Tubes.—As shown by the symbol of the voltage-regulator tube 2 in Fig. 10*I*, it has an anode and a cath-

ode;* however, no filament is used and the cathode is not heated. Such a cold-cathode tube shows a colored glow (red for neon gas, purple for argon, etc.) as soon as the starting voltage is applied to the tube terminals. The cathode, or negative electrode, glows more brightly as more electrons cross to the anode. In any such gas- or vapor-filled enclosure, some of the gas particles are already charged (ionized[9-2]); when the starting voltage is applied, these charges move with enough speed to ionize the other particles and supply the needed flow of electrons. However, without enough starting voltage, the tube acts as an open circuit; if the voltage across the tube becomes less than its working voltage, so that the tube's electron flow becomes too small, the tube again becomes an open circuit.

The cold-cathode tube 2, in the d-c circuit of Fig. 10*I*, is asked to pass current in only one direction. Since both the anode and the cathode are cold, we might expect that electrons would be emitted equally well from either electrode and that this tube does not naturally rectify. However, most regulator tubes have large cathode surfaces and small anodes, so that lower voltage is needed to cause electron flow from cathode to anode than in the opposite direction.

A small neon or argon glow lamp is also a cold-cathode tube, and may act as a voltage regulator. Such a lamp may have two electrodes of equal size and shape; either electrode may glow, but only when that electrode is much more negative than the other electrode. With a-c voltage applied to such a lamp, both electrodes glow; in a d-c circuit, only the negative electrode glows. Such a lamp may serve as a signal to show that the voltage across its terminals is greater (lamp lit) or less (lamp dark) than a certain voltage.

10-8. Disk Rectifiers for D-c Power Supply.—Although not electronic, these rectifiers (copper-oxide and selenium units described in Sec. 28-13) are often used instead of electron tubes, especially when direct current is needed at less than 80 volts. A

* Although only two base pins are used for connections to tube electrodes, two other base pins may have an internal connection between them (as shown at *A* in Fig. 10*A*). If the voltage-regulator tube is removed from its socket, the output voltage (*EE* in Fig. 10*I*) may rise too high. Therefore, this circuit in the tube base, from one pin to the other, is connected into the d-c supply circuit between resistor 1*R* and point 4. Now when tube 2 is removed, there is no voltage at *EE*.

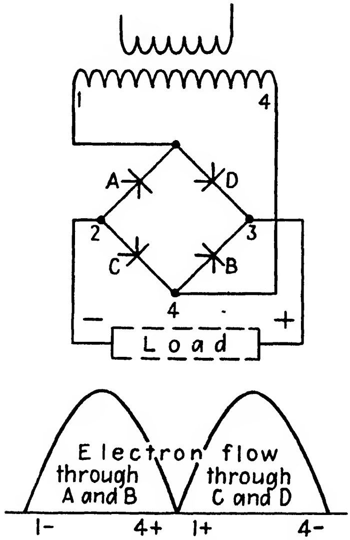


FIG. 10J.—Full-wave disk-rectifier bridge.

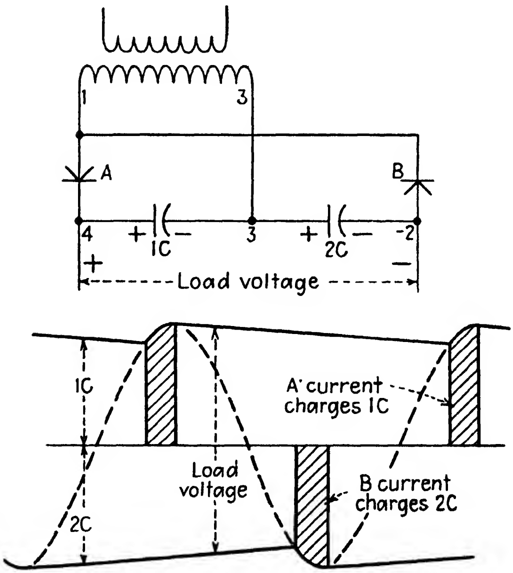


FIG. 10K. Disk rectifiers in a voltage-doubler circuit.

half-wave rectifier appears in Fig. 8*D*, where capacitor 1*C* acts as a filter to hold 80 volts for the grid circuit of tube *T*.

A common connection of disk rectifiers is shown in Fig. 10*J*, using groups of disks (each shown by the symbol ⇥|-) arranged in a four-sided bridge. Notice no center tap is used on the anode transformer. When transformer terminal 4 is positive, electrons flow from terminal 1, through rectifier *A* to point 2, through the load to point 3 and through rectifier *B* to terminal 4. During the next half cycle, electrons flow from 4 through rectifier *C* to point 2, through the load and rectifier *D* to point 1. A similar arrangement of four tubes is described in Sec. 20-6.

Another arrangement, shown in Fig. 10*K*, uses disk rectifiers in a voltage-doubler circuit. (Figure 5*D* is a similar circuit, using tubes.) When transformer terminal 1 is positive, electrons flow from terminal 3, charging capacitor 1*C* and returning from point 4 through rectifier *A* to 1. During the next half cycle, electrons flow from terminal 1 through rectifier *B* to point 2, charge capacitor 2*C* and return to terminal 3. Each capacitor charges to the crest[5-6] of the transformer 1-to-3 voltage, so the total voltage supplied to the load averages nearly twice this crest voltage.

Questions

1. Near tube 1 in Fig. 10*A*, if voltage *B* is never greater than 130 volts a.c., how much current flows in tube 2?

2. In Fig. 10*I*, if resistor 1*R* is changed to 400 ohms, what effect will this have on tube 2?

3. In Fig. 10*J*, if rectifier *A* is shorted, what change occurs (*a*) in the voltage across the load? (*b*) in the current through *D*? (*c*) in the current through *B*?

4. Assume that the transformer supplies 600 volts in Fig. 9*B* (between 3 and 5), or supplies 400 volts in Fig. 10*J* (between 1 and 4), or supplies 300 volts in Fig. 10*K* (between 1 and 3). Draw sketches to show which load receives the largest voltage. Which receives the smallest voltage? (Assume zero loss or drop in the tubes and rectifiers.)

True or false? Explain why.

5. A voltage-regulator tube is a thermionic triode.

6. A center tap is needed on an anode transformer that supplies (*a*) a two-tube rectifier; (*b*) a four-tube bridge rectifier.

7. All vapor-filled tubes have about 15 volts drop.

CHAPTER 11

THYRATRON TUBES

Hot-cathode tubes containing mercury vapor or gas are described in Chap. 9, where they are used mainly as rectifiers, and called *phanotrons*. Such a vapor-filled tube can be controlled by adding a grid; this grid-controlled gas tube is the *thyratron*, perhaps the most important tube of industrial electronics.

11-1. Can a Thyratron Replace a Pliotron?—A small thyratron may have the same size, appearance and socket connections as a high-vacuum, or pliotron, tube. So why not try a thyratron in place of the pliotron T in the d-c photoelectric relay of Fig. 3G? For convenience, this diagram is shown again in Fig. 11A. First let us recall the circuit operation, while T is a high-vacuum tube. A gradual increase in light and phototube-P current gradually raises the grid potential of tube T, increasing its anode current until CR is picked up. If the light then decreases, phototube P lowers the grid potential of tube T, which decreases the current through CR coil until CR drops out.

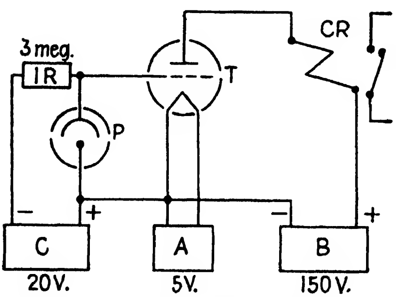


Fig. 11A.—May tube T be a thyratron?

Now substitute a thyratron tube in place of pliotron T. We observe that the thyratron's filament becomes red hot, just like the pliotron's filament. We also find that the thyratron passes no current if the phototube has been kept dark, keeping the thyratron grid negative. When enough light strikes the phototube, the thyratron suddenly passes current, energizing relay CR. A faint purple glow is seen in the thyratron. We now darken the phototube, but find that it cannot shut off the thyratron or drop out CR. Since the circuit of Fig. 11A operates on direct current, the only way we can stop the thyratron's current flow is by open-

ing the anode circuit (as by disconnecting battery B). After so stopping the tube current and restoring connections, we find that the dark phototube has regained control and prevents the restarting of the thyratron. Very gradually increasing the light on the phototube, we detect no sign of tube current until very suddenly it again passes full current and picks up CR, and again the phototube has lost its power to control the thyratron. These observations make us curious, and we need an explanation.

11-2. Thyratron Performance.—We already know the main difference between the thyratron and the pliotron—the thyratron has a gas or a vapor inside. Both tubes produce electrons from a heated filament or cathode; each requires that its anode be positive, to cause current to flow; each can prevent the start of current flow if its control grid is sufficiently negative. The difference between the tubes appears only when the current has started to flow. In the high-vacuum type, we learned[7-3] that the current flow consists of millions of electrons streaming from the heated cathode, and that this flow of electrons can be increased or decreased by changing the potential of the grid. In the thyratron, the electrons can be similarly repelled by the grid, to prevent the start of current flow. But when the grid has permitted a few electrons to start their trip toward the anode, another action occurs. As described in Sec. 9-2, the gas becomes ionized—each gas particle itself becomes able to help the electrons flow toward the anode. In football language, the gas particles become blockers, to run interference for the electrons and to prevent the grid potential from reaching or influencing the electron flow. With this help from the ionized gas particles, which decreases the resistance to electron flow, billions more of electrons are able to reach the anode than would be possible in the same tube if the gas particles were not present. Therefore, the vapor-filled thyratron is rated to carry larger values of current, in contrast to smaller values carried by the same size of high-vacuum tube.

When the thyratron starts to pass current, it immediately swings into full action, passing all the current that its external load circuit will permit. The thyratron has a trigger action similar to a mousetrap, and cannot be reset or turned off merely by working the trigger. In contrast, the high-vacuum pliotron (similar to most radio tubes) acts more like a water faucet or a valve, which controls the amount of flow and retains the power

to shut off the flow entirely. So, by substituting a thyratron in Fig. 11A, we obtain snap action (so that the tube passes full current when the grid potential rises to some critical value). At the same time, we lose the power to turn off the tube and reset CR, but that will not bother us when we see later how the thyratron works on alternating current.*

Figure 11B shows the critical value of grid potential that permits one kind of thyratron† suddenly to fire or pass current. For example, the slanting line shows that, with grid potential of −4 volts, the tube passes no current when anode voltage is 300, but it passes total current when the anode voltage rises to 400. Similarly, holding 400 volts steadily at the anode, this thyratron does not fire when its grid potential is −5 volts, but it fires suddenly when the grid potential is raised to −4 volts.

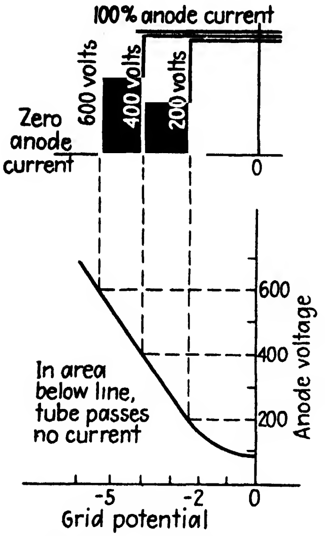


FIG. 11B.—Tipping point or critical grid potential of a thyratron.

11-3. A Thyratron Photoelectric A-c Relay.—Now we are ready to watch the thyratron operate in an a-c circuit. Figure 11E includes the thyratron and phototube in the circuit of a photoelectric relay, such as is shown in Fig. 11C. In the preceding discussion, light falling on the phototube turned on the thyratron. In this circuit (Fig. 11E), a decrease of light turns on the thyratron and energizes the relay. (The dot shown inside the tube indicates that the tube contains gas or vapor and gives a clue to its operating characteristics.)

Like other tubes, the thyratron acts as a rectifier, so tube B in Fig. 11E can pass current only during the half cycle when trans-

* D-c anode voltage may be purposely used with a thyratron, so that it will continue to fire until reset by opening its anode circuit.[22-4]

† The curve of Fig. 11B applies to a *negative-control* type of thyratron, for its grid must be kept more negative than its cathode, to prevent anode current from flowing. In contrast, a *positive-control* thyratron has no anode current until the control grid is made more positive than the cathode.[16-2]

former terminal 2 is positive. Such electrons flow from terminal 3, through tube *B* and *CR* coil to 2. The a-c supply to tube *B* is shown in Fig. 11*D*, wherein the voltage of half cycles 1 and 3

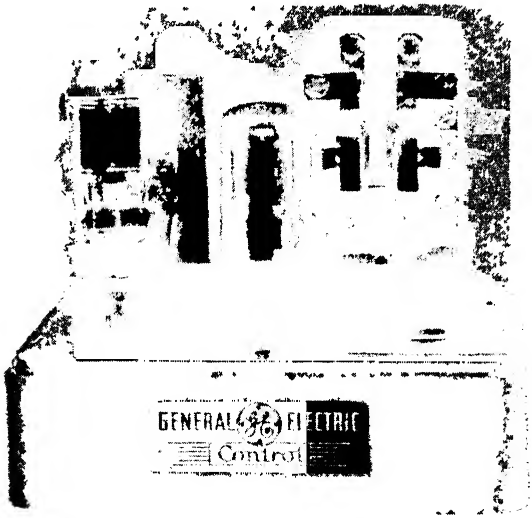


FIG. 11C —Photoelectric relay (CR7505-K100, cover removed).

can force anode current through tube *B* (if its grid is willing), but the voltage of half cycles 2 and 4 cannot produce any flow of anode current, for here the anode is more negative than the cathode.

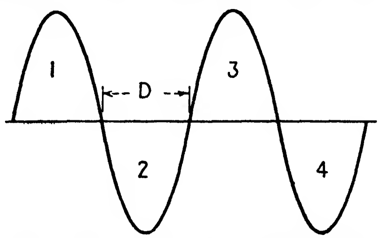


FIG. 11*D*. A thyratron's grid regains control during *D*

Suppose that the grid permits thyratron *B* to pass current during half cycle 1, but the grid becomes much more negative during the interval marked *D*. Does thyratron *B* continue to pass current during half cycle 3 also? Remember our earlier experience with the d-c circuit of Fig. 11*A*, where we were unable to regain light control of the thyratron current, once it was started by its grid. Similarly, in Fig. 11*D*, when the thyratron is permitted to start current flow at any point in half cycle 1, its grid is powerless to stop current flow during that entire half cycle. But notice that in half cycle 2 the negative anode voltage stops

the tube current just as effectively as if we disconnected the anode circuit for the same length of time. Therefore, during interval *D*, the thyratron tube has enough time to return to its original condition. This means that, with tube current temporarily stopped, the gas particles lose their ionization, or charge. By the time that anode voltage returns at the beginning of half cycle 3, the grid has regained its control over the electrons and can prevent the thyratron from starting to pass current.

So we see that, when operating on 60-cycle a-c power supply, the grid is given 60 chances each second to permit or to prevent current flow in the thyratron. Most thyratrons need about $\frac{1}{1000}$ second for deionizing the gas.* If the anode voltage returns before the gas particles completely regain their normal inactive condition, the tube immediately fires, disregarding its own control grid.

11-4. Thyratron Control by Phototube.—Returning now to Fig. 11*E*, we find thyratron tube *B* waiting to be told by its grid (not more than once each cycle) whether it is to pass anode current or not. Let us see what is happening in the grid circuit of tube *B*. Here we find phototube *A*, which passes current only when light shines on its rounded cathode. With no light, there is no current, and phototube *A* acts as an open circuit. Since no current now flows through 1*R*, the grid of tube *B* is at the same potential as its cathode 3, so tube *B* passes current during each positive half cycle; when 2 is (+), 3 is (−). We must recall that when enough light shines on phototube *A* so that it passes current, the phototube also acts as a rectifier. (Since only its cathode is made of light-sensitive metal, the electrons released by light can flow in only one direction in the tube, and this occurs only during the half cycle when the phototube anode is positive.)

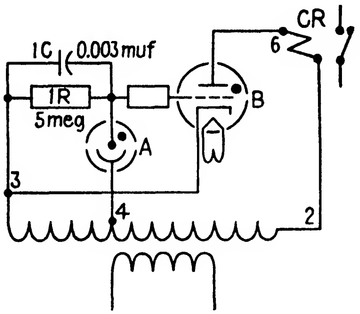


FIG. 11*E*.—Phototube relay using a thyratron.

Figure 11*E* shows that the cathode of phototube *A* is connected

* This "deionization time" is the length of time that must pass (after anode current stops) before the grid or ignitor can regain control of the vapor-filled tube.

to the supply transformer at point 4, whose potential is somewhere between that of terminals 2 and 3. Therefore, during those half cycles (1 and 3 in Fig. 11*D*) when tube *B* can pass current, we find that the cathode of phototube *A* is more positive than its own anode, so *A* cannot pass current during these half cycles, whether it is illuminated or not.

However, during half cycles 2 and 4 (when transformer terminal 3 is more positive than terminal 2, and tube *B* never fires) current can pass through phototube *A* if light reaches it. This electron flow is from transformer terminal 4, through the phototube and 1*R*, to point 3. This flow produces voltage drop across 1*R*, which becomes more negative on the end nearest the grid of tube *B*. Capacitor 1*C* is charged to the crest[5-6] of this half-wave voltage across 1*R*, and 1*C* holds enough of this charge throughout the following half cycle to keep the grid of tube *B* more negative than its cathode 3. With sufficient light on phototube *A*, the resulting charge on 1*C* is so great that tube *B* is prevented from passing current, and *CR* drops out. If the light then decreases, reducing the phototube current and the voltage across 1*C*, a point is reached where the grid voltage becomes close enough to the cathode to fire tube *B*.

11-5. The Critical Grid Voltage.—At this point we must see more clearly just what value of grid voltage permits this thyratron to fire, when operating with a-c supply. We saw this critical grid voltage in Fig. 11*B*, so we draw this curve again in Fig. 11*F*, but plot the grid voltage at a scale more nearly the same as the anode voltage. If we now draw a half sine wave of a.c. to represent the changing anode voltage of the thyratron, we can obtain a new critical-voltage* curve in Fig. 11*F* to correspond to

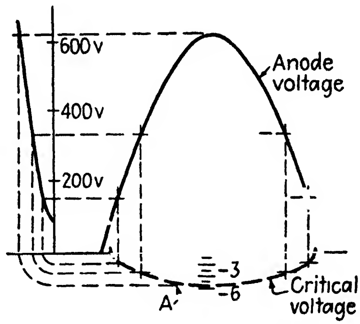


FIG. 11*F*.—Critical grid voltage of a thyratron with a-c supply.

* This potential, which the thyratron grid must have so as to prevent the flow of anode current, is called the *critical voltage* of the tube. For most thyratrons, this critical voltage is so close to zero that, in most diagrams in this book, it will be assumed that the thyratron may fire or pass current only when its grid potential becomes zero or slightly more positive than the cathode potential.

this a-c anode voltage. In Fig. 11*F* we see that a grid bias or potential of only −3 or −4 volts will prevent the thyratron from firing near the start of the half cycle. A grid bias of −5 volts prevents this tube from firing until point *A* is reached, and then the thyratron passes current for the rest of that half cycle.

11-6. Thyratron Grid-circuit Action.—Returning to our photoelectric relay circuit, Fig. 11*G* shows the anode voltage of thyratron *B*, its critical-grid-voltage curve, and the actual thyratron grid voltage (curves marked 1, 2 and 3) produced by several values of light on the phototube. A large amount of light on

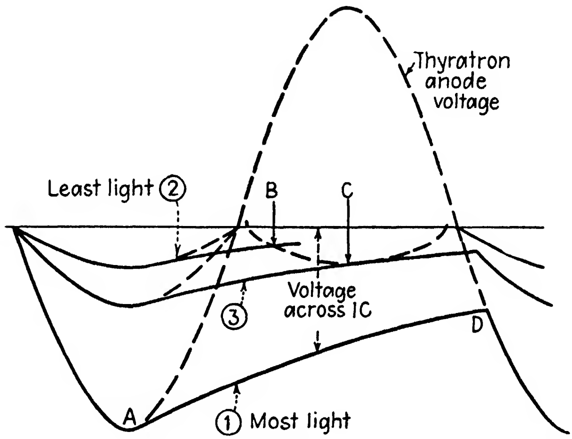


FIG. 11*G*. Voltages controlling thyratron *B* of Fig. 11*E*.

the phototube produces curve 1. During the quarter cycle preceding point *A*, capacitor 1*C* charges to such a large voltage that it holds the grid of thyratron *B* far more negative than the critical-voltage curve.* In contrast, curve 2 is produced by very little light and phototube current, resulting in very little charge on 1*C*. At point *B* in Fig. 11*G*, where curve 2 crosses the critical-grid-voltage curve, thyratron *B* passes current, which flows during the rest of the half cycle. This set of curves is repeated during each positive half cycle as long as the light on the phototube remains unchanged.

* For use in drawing Fig. 11*G*, how do we know or determine the slope of the grid-voltage curve between *A* and *D*? From the time constant (see Sec. 4-5), which equals $1R \times 1C$, or 5 megohms $\times$ 0.003 microfarad = 0.015 sec. This tells us that 0.015 sec or 0.9 cycle is the time required for the voltage across 1*C* to decrease to about one-third of its starting value.

Between curves 1 and 2 in Fig. 11*G* there must be other curves, such as curve 3, produced by a medium amount of light on the phototube. Curve 3 shows that the phototube current has charged capacitor 1*C* to a medium voltage, and this curve crosses the critical-grid-voltage curve at *C* and fires the thyratron near the middle* of the half cycle. Since thyratron current flows for only the latter part of the half cycle, relay *CR* is only partially energized. To avoid this condition, and to provide more positive pickup of *CR*, a circuit refinement is next added.

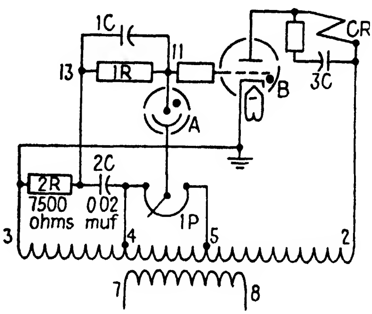


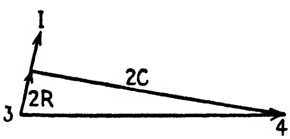
FIG. 11*H* Complete circuit of phototube-thyratron relay (CR7505 K100).

11-7. Firing the Thyratron Early.—This feature is not shown in simpler Fig. 11*E*, but appears in the complete circuit Fig. 11*H*, where 2*R* and 2*C* are added in the grid circuit of thyratron *B*. A small voltage appears across 2*R* and is added to the voltage applied to the thyratron grid. As is shown in Fig. 11*I*, this voltage† across 2*R*, when added to the dotted line of 1*C* voltage, produces a new (solid-line) curve of grid potential. Notice that this solid line crosses the critical-grid-voltage curve very early in the half cycle, or not at all. As a result, the thyratron is made to pass current for almost the entire half cycle or not at all; the coil of *CR* either is energized by full voltage or is not energized at all.

A similar feature appears in the center of Fig. 8*E*, where the Phototroller circuit includes resistor 6*R* and capacitor 2*C*, con-

* Notice how the grid, while negative, prevents any flow of the thyratron's anode current until part of the half cycle has passed. This delayed action is discussed in Chap. 13.

† As is explained in Sec. 13-5, this connection of 2*R* and 2*C* across transformer winding 3-to-4 may be shown by this vector triangle. Current *I*, flowing through 2*R* (7500 ohms) and 2*C* (which capacitor represents $1{,}000{,}000/2\pi fC$ (mu f) or 132,500 ohms at 60 cycles), is seen to lead the transformer voltage 3-to-4 by almost 90 degrees. The size of the voltage across 2*R*, which is in phase with current *I*, is seen to be small compared with other voltages in this circuit.



nected across the 10-volt transformer winding 9-to-8. In Sec. 8-4, you are not told that tube T of Fig. 8E is a thyratron. To make sure that this thyratron T fires early in its half cycle of anode voltage, or not at all, the grid circuit of T includes this "ripple" voltage, which raises the grid potential near the start of the half cycle, but lowers it to prevent firing near the end.

As another example, Fig. 10A includes thyratron tube 5, whose grid circuit[10-3] contains the secondary winding of transformer 2T, between points 7 and 10; this "ripple" a-c voltage helps to fire

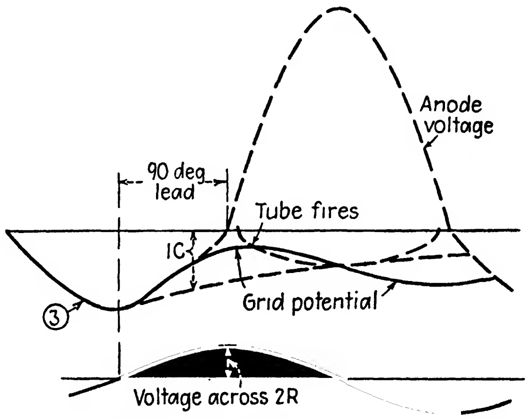


FIG. 11*I*.—Voltages controlling thyratron *B* of Fig. 11*H*.

tube 5 during the first portion of the half cycle of anode voltage, or prevents it from firing at all.

Details such as those described above are frequently met in tube-operated circuits. These examples warn us that further study of electronics will require not only a general knowledge of electron-tube behavior, but must also include greater familiarity with our old friends the capacitor, the reactor and other standard circuit elements.

11-8. Using This A-c Photoelectric Relay.—The complete circuit, Fig. 11H, of the general-purpose photoelectric relay includes a potentiometer 1P, which may be adjusted so that the relay will operate at the desired light intensity at the phototube. When 1P is turned closer to 4, then 1R and phototube A are connected across a smaller portion of the transformer supply voltage 3-to-5; a greater amount of light must reach the phototube in order to drop out relay CR.

To apply this particular photoelectric relay properly, there must be sufficient light on the phototube during the 30-sec warming period to prevent thyratron B from passing current. Otherwise, thyratron B tries to pass anode current before its cathode is hot enough to furnish the necessary electron flow. Repeated warming with a dark phototube will damage this type of thyratron cathode and will decrease the tube life.

Figure 11H shows that phototube A is of the vapor-filled or gaseous type (shown by the dot inside the tube symbol). As would be expected (from the previous comparison of high-vacuum and vapor-filled triodes), a vapor-filled phototube can pass more current than can a high-vacuum phototube; the vapor-filled type is more generally used in industrial circuits. Either type of phototube responds immediately to light changes. However, the power supply and circuit surrounding the phototube determine how fast the whole photoelectric relay can respond to light changes. This general-purpose relay does not respond to a light change lasting less than ⅕ sec. Another type of photoelectric relay, designed for high-speed impulse-trip operation, is discussed in Sec. 22-2.

11-9. Effect of Thyratron Temperature and Grid Construction. Most texts in electronics devote many pages to these subjects, which are so important to circuit design. Let us merely note several points of interest. Figure 11B shows a single slanting line, to indicate the grid potential that lets a thyratron fire; if this thyratron is of the usual mercury-vapor type, then this slanting line is correct only when the coolest part of the tube enclosure is at perhaps 40°C. If the tube temperature rises 20 or 30 degrees, the slanting line of Fig. 11B must move to the left; we must now apply 1 to 2 volts lower (more negative) grid potential, to keep the tube from firing. This temperature effect does not occur in thyratrons filled with gas like argon.

At high temperatures, thyratrons (and phanotrons) will not rectify well with high anode voltages; at very low temperatures these tubes may not produce the large flow of electrons required, and this may cause higher arc drop and erratic operation. These factors show why, for best results, the gas- or vapor-filled tubes must operate at medium temperature.

The grid of a high-vacuum tube may be merely a wire mesh, which can prevent most electrons from reaching the anode.

However, in a thyratron, the grid must prevent all electron flow; if some electrons escape to the anode, they will ionize the gas particles so that the grid can no longer prevent the main flow of anode current. Therefore, the thyratron grid is usually a metal cylinder large enough to enclose the cathode and part of the anode, as shown in Fig. 11*J*; when this large grid surface is sufficiently negative, all electrons are repelled and cannot reach the anode. This grid surface helps also to contain the cathode heat and to shield the cathode from unwanted stray-field effects. However, so large a grid structure permits the flow of greater grid current and is directly affected by sudden changes of anode voltage and by the heat and material of the cathode. In spite of these effects, this single-grid thyratron (or vapor-filled triode) is widely used.*

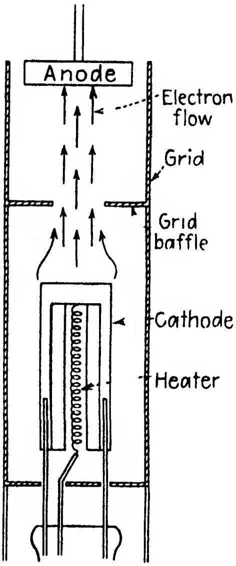


FIG. 11*J*.—Parts inside a thyratron.

11-10. The Shield-grid Thyratron.—By adding a second grid, we produce a tetrode thyratron, which has much less grid current and is more sensitive to its grid signal. As shown in Fig. 11*K*, the large metal grid enclosure is now called the *shield grid*, and a separate small control grid is added. Notice how the shield grid† encloses or shields the control grid from the heat or material of the cathode and also from the anode voltage; yet the small control grid can prevent all flow of electrons through the central opening in the shield.

The shield grid is usually connected to a base pin; outside the tube, the shield grid is often connected to the tube cathode. So connected, this thyratron has nearly the same operation as is shown in Fig. 11*B*. Therefore, when the shield grid is connected to the cathode, we may omit this extra grid from our circuit dis-

* Examples are the FG-17, KU-627, GL-393, WL-631 and FG-57 thyratrons.

† This added grid should not be confused with the screen grid of a high-vacuum tube, whose operation is similar only with respect to decreasing the interaction between anode and control grid.

cussion. However, if the shield grid is connected to a point in the circuit that is a few volts more positive than the cathode, this has the same effect as moving the slanting line of Fig. 11B to the left; a more negative control-grid potential is needed, to prevent the

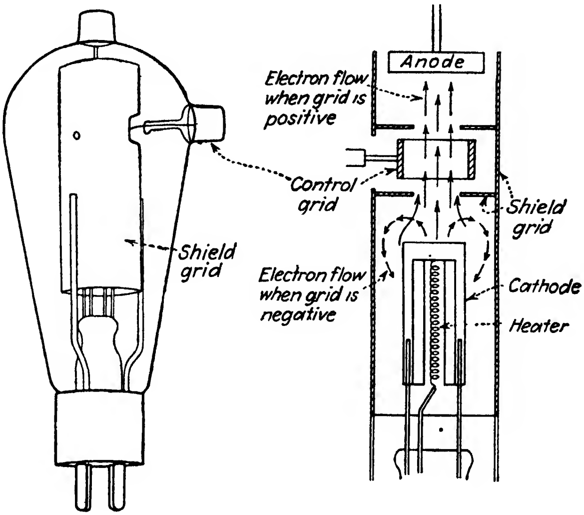


FIG. 11K.—Shield-grid thyratron.

tube from firing. Similarly, if the shield grid is made more negative than the cathode of the thyratron, then the control grid must be made less negative, to let the tube fire; if the shield grid is 10 or 15 volts negative, this tube becomes a positive-control thyratron, whose anode current does not flow until a positive signal is applied to the control grid.

Symbols of shield-grid tubes appear in Fig. 11L; (a) is used for tubes with glass envelopes, (b) applies to all-metal thyratrons, such as the FG-172 or the GL-414, in which the shield grid is connected to the metal outer shell of the tube, which is connected to the cathode.

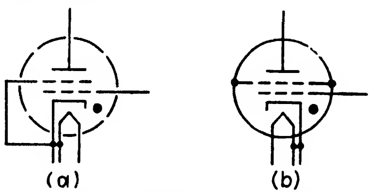


FIG. 11L.—Symbols of a shield-grid thyratron.

11-11. Positive Grid Voltage.—When anode current is flowing through a mercury-vapor-filled thyratron, the anode voltage is 15 to 20 volts, as has been already explained.[9-3] Similarly, the

grid voltage (measured between grid and cathode) may be several hundred volts when no grid current flows; however, as soon as the grid becomes 15 volts more positive than the cathode there is a small flow of electrons through the tube from cathode to grid. This positive grid voltage cannot be greater than the arc drop through the tube, so any excess positive grid voltage appears across a resistor in the grid circuit.

Questions

1. When a thyratron is supplied with d-c anode voltage, which of the following are true? Explain.

a. The grid does not have control of the starting of anode-current flow.
b. Anode current will not stop until anode voltage is removed.
c. To cause the anode current to decrease, the grid must be made slightly more negative than when a-c anode voltage is supplied.
d. The same amount of bias will prevent the starting of anode current, with either a-c or d-c anode voltage.
e. Anode current flows only as long as the grid potential is above the critical voltage.
f. With constant anode voltage, the critical voltage is not a curve, but is constant.

True or false? Explain why.

2. For heating the filament, a.c. is better than d.c.

3. Decreased heater voltage will damage a thyratron more than a pliotron.

4. The main reason for using a large grid cylinder around the thyratron cathode is to hold the heat inside.

5. A thyratron should not be used if the anode current is less than $\frac{1}{10}$ ampere.

6. Shield grid is another name for a screen grid.

7. By raising its filament current, a thyratron may carry larger peak anode currents.

8. For use outdoors, a gas-filled tube may work better than a mercury-vapor-filled tube.

9. The critical-voltage curve is made more positive by making the shield grid more positive.

10. A screen grid is often connected to the anode, while a shield grid is often connected to the cathode.

11. When the control grid is connected to the cathode, the thyratron may be turned on by the shield grid.

12. A thyratron has twice as much voltage drop (anode to cathode) when passing twice as much current.

13. A thyratron passes anode current only when its cathode is at lower potential than its anode.

14. Two thyratrons may be enclosed in one shell to act as a duplex tube.

15. Most tetrode thyratrons may be fired by a more positive impulse at either the shield grid or the control grid.

16. Operating on d-c anode voltage, a negative shield grid may turn off the thyratron anode current.

CHAPTER 12

RESISTANCE-WELDING CONTROLS

The tube control of spot welders and seam welders shows that industrial electronics has been of great value and interest for at least 15 years. Types called *synchronous* controls by their extreme accuracy now make it possible to weld together metals that were never welded before These welding-control equipments are used in thousands of industrial plants and they deserve a prominent place in this book. However, since many of these weld timers and synchronous controls are described and explained in another book,* only a few such welder controls are included here.

12-1. Resistance Welding. —Two pieces of metal may be welded or fused together by passing large current (1000 to 100,000

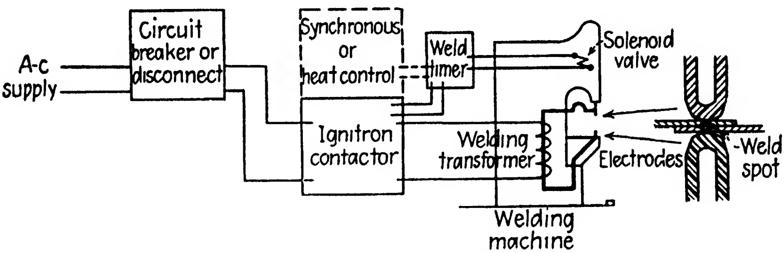


FIG. 12A Welding machine and its electrical equipment

amperes) through these pieces, while they are being forced together between the electrodes of the welding machine.† Figure 12*A* shows how the 220- or 440-volt a-c supply passes through a protective device, then through a contactor, before reaching the welding machine. In the machine, a welding transformer reduces the voltage at the electrode tips to 1 to 10 volts, and supplies the large welding current, while drawing perhaps 50 to

* CHUTE, G. M , "Electronic Control of Resistance Welding," McGraw-Hill Book Company, Inc , New York, 1943.

† When pieces of metal are being joined or welded together by a bright electric arc, which melts a rod into a pool of metal, that is called *arc welding.* Tube control of arc-welding equipment is described in Chap 16.

2000 amperes from the a-c supply. To make a weld, current needs to flow for only part of a second;* the contactor must close and open the circuit quickly, and it does this hundreds of times each hour. While magnetic contactors control many such welders, ignitron contactors and other electron-tube equipments are used where better welds must be made in shorter time, with less contactor noise and maintenance.

To make a single spot weld, the pieces of metal are placed in the space between the two electrodes, one of which can move. When the operator presses the button or the foot switch, the electrodes come together and squeeze the metal pieces. Welding current then flows to heat the metal and make the weld. The metal is held under pressure for a moment until the weld hardens, then the electrodes separate so that the metal can be moved before the next weld is started.

To control such a welding machine, notice that four lengths of time (perhaps from 3 to 30 cycles each) must be measured, such as by using four time-delay relays.[6-1] After the foot switch is closed, the *squeeze time* permits the electrodes to build up the right pressure on the work. The *weld time* is the length of time during which the welding current flows. After the welding current stops, the electrodes continue to press against the metal pieces during the *hold time*, while the weld hardens. Then the electrodes separate; if the operator still holds the foot switch closed, the electrodes will reclose after a period called the *off time*, which gives time to move the work or insert new pieces of metal between the electrodes.

12-2. Controls for Resistance Welding.—As is shown in Fig. 12*A*, an ignitron contactor[9-10] may control or switch the alternating current supplied to the welding transformer. This pair of

* To make a weld, the required heat $H = I^2RT$, or heat equals

(current) × (current) × (resistance between the pieces welded)
× (time while current flows).

Since there must be resistance to current flow between the metal pieces, where most of the weld heat is produced, we call this process *resistance welding*. This resistance depends on the metal that is being welded; steel has high resistance, so welding heat is easily produced; aluminum has low resistance, and the welding heat is harder to obtain. Further, this resistance between the metal pieces decreases when they are forced together by the electrodes with greater pressure.

ignitron tubes by itself produces no better welds than a magnetic contactor, except that the tubes may handle thousands of amperes for a time as short as one cycle. However, this pair of ignitrons may be controlled by other tube-operated circuits. To change gradually the amount of welding heat, by merely turning a small dial, a pair of phase-shifted thyratrons is added as in the heat-control equipments described in Chap. 13. To get better welds, by accurate synchronous control, other tube-operated accessory panels may be added to the ignitron contactor, as indicated in Fig. 12A; or a single larger synchronous-control equipment may be used, mounting the ignitron tubes inside.

For seam welders, which use roller electrodes to produce a continuous or stitch weld made of overlapping welded spots, the same pair of ignitron tubes may be used, but controlled by other tube circuits to produce the *heat* and *cool* times (similar to wéld time and time between welds while the roller electrodes remain pressed on the work). Electronic heat control by the phase-shift heat method[13-8] is usually included in such seam-welder controls.

A welder equipment that includes electronic heat control can be made to regulate for variations of a-c supply voltage or can be made to hold constant welding current, in spite of changes in the weld work. Such regulators, which are separate all-tube equipments, to be combined with other electronic welding controls, are described in Chap. 26.

Small spot welders may make each weld by using the a-c supply for only a half cycle, by once firing a single ignitron tube.[12-16] Other small welders may need so little alternating current that ignitron tubes are not used, but the welding-transformer primary current is switched through a pair of thyratron tubes.[12-11]

So far, all the welder equipments mentioned aim to control only the flow of a.c. to the welding transformer. To operate the electrodes of the welding machine, and to "tell" the above control equipment when to pass current into the weld, a sequence control is used. The circuits of several sequence timers are described below.

We have mentioned only a-c resistance welding—the type that connects one phase of the a-c power supply directly to the welding transformer for a short time, to produce the flow of welding current. Another type is energy-storage welding; here the a-c

supply (usually three-phase) is rectified to produce direct current, which stores energy in a bank of capacitors or in a special transformer. When this energy is released, to cause the flow of welding current, this current does not alternate or cause a sudden inrush of current from the a-c supply line. Rectifier circuits for such energy-storage welders are described in Chap. 18.

12-3. A Sequence Weld Timer (CR7503-F118).—This timer is a combination of several tube-operated time-delay relays, along with other relays that control the welding contactor and the welder electrodes so as to give the correct squeeze time, weld time, hold time and off time, already mentioned.[12-1] The elementary diagram of this automatic weld timer is shown in Fig. 12*B*. Starting at the top, the secondary winding of transformer 1*T* gives 115 volts between 1 and 3, if the 1*T* primary is correctly connected to the supply voltage. When the operator closes the starting switch 1*S*, this completes the circuit to the coil of 1*CR*, which closes its contact 7*A*-to-7*B*, to energize the solenoid valve (shown at the right).

In Fig. 12*B*, each of the four time-delay circuits is shown merely as a rectangle, marked like 1*TD* or 4*TD*. Each rectangle shows only three connections to the time-delay circuit that it contains. Connections 1 and 3 furnish the 115-volt a-c supply to all these circuit parts, and 16 or 46 is the connection that starts the circuit to give its time-delay action. For example, when the circuit is closed to point 16, then 1*TD* starts to time the squeeze time, which is set for perhaps 7 cycles. After this 7 cycles of time, the relay in this circuit operates its contacts. These contacts are not shown inside the rectangle of 1*TD*, but appear farther down in the diagram, in the circuits to 2*CR* and 4*TD*. This shows that, when 1*TD* times out or operates its relay contacts, one of these 1*TD* contacts energizes 2*CR*, while the other 1*TD* contact closes the circuit to point 46, which then starts 4*TD* to measure its weld time.

When you need to know the detailed operation of the time-delay circuit inside one of these rectangles, you will find this circuit in the lower right-hand corner of Fig. 12*B*. This shows the parts inside the 4*TD* rectangle, but it applies as well to the other rectangle circuits. Although this circuit is explained in Chap. 6, we repeat it here, using the 4*TD* circuit shown in Fig. 12*B*.

12-4. How Each Time-delay Circuit Works.—While the starting contact is open (1*TD* is the starting contact for rectangle 4*TD*), no electrons flow through tube 4, 48*R*, and coil 4*TD* to point 3, because the cathode 46 is not connected to the other side 1 of the a-c supply. At this same time, electrons flow from 3

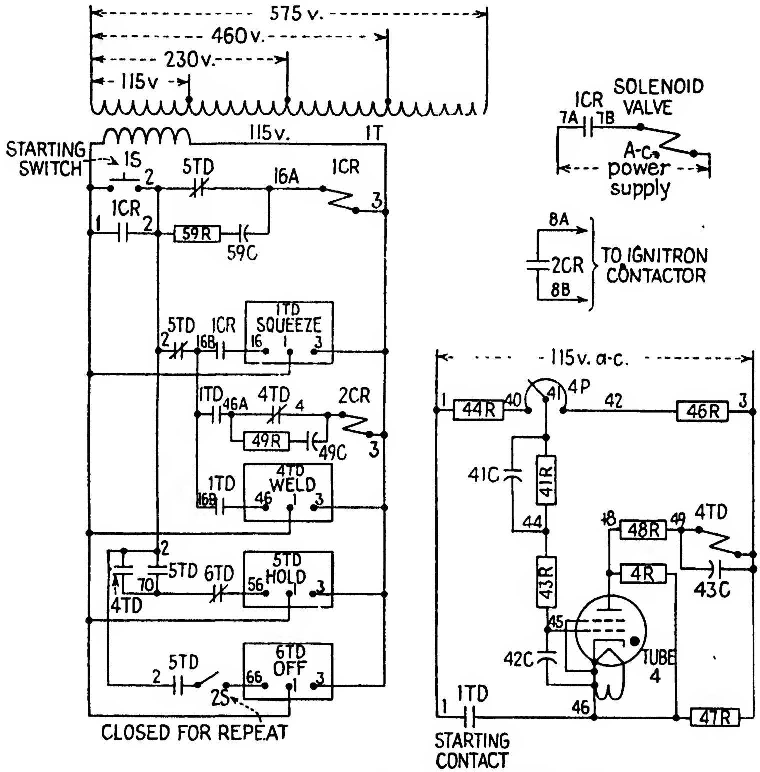


FIG. 12*B*.—Sequence weld timer (CR7503-F118).

through 47*R*, cathode to grid of tube 4, through 43*R* and 41*R* to slider 41. By grid rectification[5-4] this flow is in only one direction and charges capacitor 41*C* to the crest value[5-6] of the voltage across 41*R*, which is slightly less than the voltage between slider 41 and point 3. This timing capacitor 41*C* remains charged as long as the starting contact remains open and keeps the tube-4 grid more negative than slider 41. When the starting contact is closed, the circuit is completed from 1 to cathode 46, through tube 4 and 4*TD* coil to point 3, but tube 4 still cannot pass

electrons through this circuit because of the negative voltage bias on tube-4 grid. However, as the time passes for which the slider of *4P* is adjusted, the charge on *41C* decreases, because it discharges through *41R*. When this *41C* charge is no longer large enough to keep the grid of tube 4 negative, this tube fires and picks up relay *4TD*, operating the *4TD* contacts shown in the main portion of Fig. 12*B*.

The action of this grid circuit is shown in Figs. 6*B* to 6*D*. Tube 4 in Fig. 12*B* is a thyratron (the GL-502 or GL-2051 shield-grid[11-10] type), and fires instantly and completely as soon as its control grid lets it fire at all. Tube 4 continues to fire and keeps relay *4TD* energized, until voltage is removed from point 46 by opening some contact in the circuit between 1 and 46.

12-5. Operating Sequence.—Let us trace the step-by-step operation of this weld timer in Fig. 12*B*. Close switch *1S*, which completes the circuit from 1 through n-c (normally-closed) contact of *5TD*, to energize *1CR*. Then *1CR* picks up the solenoid valve and brings the electrodes together. Another *1CR* contact connects 1 and 2, sealing around *1S*, keeping *1CR* energized even though *1S* is released. A third *1CR* contact completes the circuit to 16 on *1TD* time-delay relay. This lets *1TD* measure out the squeeze time, to make sure that the electrodes have time to squeeze the work with enough pressure. After this squeeze time, *1TD* contacts complete the circuit to contactor *2CR*, which closes the ignitor circuit of the ignitron contactor, making the ignitron tubes pass current to the welder. At the same time, another *1TD* contact completes the circuit to 46, starting *4TD* to measure the weld time; after this, *4TD* opens its n-c contact 46*A*-to-4, opening the circuit to *2CR*. Then *2CR* drops out, opening the ignitor circuit and ending the flow of welding current.

Weld timer *4TD* also closes its contact 2-to-70, which completes the circuit to 56 and starts *5TD* to measure out the hold time, while the weld hardens. After this hold time, *5TD* opens its n-c contact between 2 and 16*A* (near the top of Fig. 12*B*); this drops out *1CR* and the solenoid valve and lets the electrodes separate. Although this also opens the *1CR* contact 1-to-2, the *5TD* relay is still energized through its own *5TD* contact 2-to-70, if the operator still holds *1S* closed. However, if *2S* (bottom of Fig. 12*B*) is open for nonrepeat welding, the welder will not work again until the operator releases *1S* and then closes it again.

Here 1*S* opens the circuit to 5*TD*, letting 5*TD* drop out and reclose its n-c contact 2-to-16*A*. When 1*S* is again closed by the operator, a new weld sequence is started to make another spot weld.

If 2*S* is closed, to give repeat welding, the whole sequence is the same as above, to the time when 5*TD* operates its contacts. Now with 2*S* closed, 5*TD* not only drops out 1*CR*, but another 5*TD* contact completes the circuit through 2*S* to 66, which starts 6*TD* to measure the off time during which the electrodes are away from work. Another 5*TD* contact seals across 2-to-70 so as to keep 5*TD* energized even when 4*TD* drops out. (4*TD* is dropped out by the opening of 5*TD* n-c contact 2-to-16*B*.) Of course, there is no circuit to make 6*TD* work if the operator is not holding 1*S* closed at this time. If 1*S* is still closed at the end of the off time, 6*TD* operates its one contact, which is n-c, between 70 and 56. This 6*TD* contact drops out 5*TD*. This lets 5*TD* reclose its n-c contact 2-to-16*A* (near top) and energize the solenoid valve, bringing the electrodes together to start another welding operation. This complete operation will be repeated over and over, as long as the operator keeps 1*S* closed. If 1*S* is opened while the electrodes are together, the electrodes will not separate until after the usual weld and hold times have passed.

12-6. Capacitor for Arc Prevention.—In the center of Fig. 12*B*, capacitor 49*C* helps to prevent burning or arcing at 4*TD* n-c contact 46*A*-to-4. There is no voltage across capacitor 49*C* while the 4*TD* contact is closed, so 49*C* holds no charge. When this contact opens, the energy in the inductive 2*CR* coil (which would force current to cause arcing and burning) is used instead to charge 49*C* to the voltage appearing across these opened contacts. To prevent 49*C* from discharging too rapidly when the 4*TD* contact again closes, resistor 49*R* is used to limit the discharge current. Similarly, the life of the 5*TD* contact 2-to-16*A* is greatly increased by adding 59*C* and 59*R* (0.25 mu f and 50 ohms).

12-7. Grid-to-cathode Capacitor.—Near tube 4 in Fig. 12*B*, capacitor 42*C* is connected between the control grid and the cathode. Notice that the operation of the time-delay circuit of tube 4 is completely explained[12-4] without mentioning 42*C*. Such a capacitor is used with each thyratron is most industrial circuits,

to prevent the thyratron from false or unexpected operation, such as comes from sudden changes of anode voltage or from surges in the electric power system. A flicker of grid voltage lasting less than 1/10,000 sec. can easily make the thyratron pass anode current for a half cycle. This grid-to-cathode capacitor is so small (0.0001 to 0.005 mu f) that it has no effect at 60 cycles, yet it drains off the more sudden changes of grid voltage that may fire the thyratron at the wrong time.

12-8.—Another Sequence Weld Timer (Weltronic Model 75). The diagram of this timer, in Fig. 12*C*, shows that it has three time-delay circuits similar to that shown in Fig. 6*F*; it operates a welder in the same way as the timer of Fig. 12*B*. Figure 12*C* shows many connections to ground (⏚); all these grounds are connected together and become part of the circuits For example, when the starting switch is closed, the 115-volt winding of the supply transformer 1*T* forces current to flow in its ground connection, and the circuit is completed from ground through the starting switch and transformer 2*T* to point 2 and the other 115-volt terminal of 1*T*. Similarly, any current flowing in the anode circuit of tube 1 is caused by the 400-volt winding of 1*T*; while the left-hand or ground terminal of this 400-volt winding is negative, electrons flow into ground and from ground to the tube-1 cathode, to tube-1 anode, through the coil of relay 1*CR* to point 6, and through fuse 1*F* to the positive terminal of 1*T*.

The tubes in Fig. 12*C* are high-vacuum tetrodes[7-7]; tubes 2 and 3 have the screen grid connected to the anode, so that the screen is positive during the half cycle when anode current can flow; in this way, the screen helps current to pass through the tube, and the amount of this current depends entirely on the control grid. However, the screen grid of tube 1 is used as a second control grid. If there is no voltage at the screen (as when transformer 2*T* is not energized) tube 1 cannot pass enough current to pick up relay 1*CR*; when 2*T* makes the screen grid of tube 1 positive, tube 1 passes more current, as long as its control grid permits. When transformer 3*T* applies its negative voltage to the control grid, this decreases the tube-1 current, although the screen is yet positive.

Closing the starting switch completes the circuit to transformer 2*T*, which applies 200 volts to the screen grid of tube 1. Since the 3*CR* contact (below the starting switch) is not yet closed, 3*T*

is not energized. With zero voltage on the control grid, the starting switch makes tube 1 pick up *1CR*; a *1CR* contact closes next to the starting switch, so that *2T* remains energized. Farther down the left-hand side of Fig. 12*C* another *1CR* contact has closed; relay *4CR* is picked up and its contact closes the solenoid-valve circuit, which forces the electrodes onto the weld work. By the same *1CR* contact, transformer *4T* is also energized, starting the time-delay action in the tube-2 circuit, to give the squeeze time.

12-9. Grid-circuit Action in Weltronic Timer.—Recall from Sec. 6-5 that the secondary windings of transformers *4T* and *5T* are opposed. Before *4T* is energized, the 100 volts' output of *5T* causes electrons to flow through *3CA* (time-adjusting resistor and variable capacitor) to ground, from cathode to grid of tube 2 and back through *4T*; by grid rectification,[5-4] this flow charges *3CA*, negative on the end nearest the grid, which keeps tube 2 from passing current. When the starting switch closes, *4T* produces 100 volts, which bucks the 100 volts of *5T*; no voltage remains in the grid circuit of tube 2 except the charge on *3CA*. After the desired squeeze time (depending on the number of capacitors connected in *3CA*), the voltage across *3CA* has decreased so as to let tube 2 pick up relay *2CR*.

Two *2CR* contacts close (lower left-hand corner of Fig. 12*C*); one of these completes the circuit through the n-c *3CR* contact, to pick up relay *5CR*. The *5CR* contact fires the ignitron contactor, letting current flow to make the weld. The upper *2CR* contact starts the time-delay action of tube 3, by energizing transformer *6T* (as described above for *4T* and tube 2). This is the weld time; when tube 3 picks up relay *3CR*, this relay opens its n-c contact, dropping out relay *5CR* and stopping the flow of welding current through the ignitron contactor. Notice that there are two resistors in *4CA* (lower right) through which the weld-time capacitor must discharge. By the closing of switch *2S*, shorting one of the resistors, the weld time is made shorter.

After the weld time, another *3CR* contact (near the starting switch) energizes transformer *3T*. The 100 volts' output of *3T* charges *2CA*, thereby placing a negative voltage on the grid of tube 1. Although this shuts off the current of the high-vacuum tube 1, relay *1CR* does not yet drop out; the large capacitor *1CA* holds so much electricity that its discharge current keeps relay

$1CR$ picked up for part of a second, and this delayed dropout produces the hold time. (Smaller capacitors across coils of $2CR$ and $3CR$ are only to prevent relay chatter.)[5-2]

After the hold time, relay $1CR$ opens its contacts. However, if switch $1S$ (middle left) is closed, to give single welds, the operator must release the starting switch before the relays will

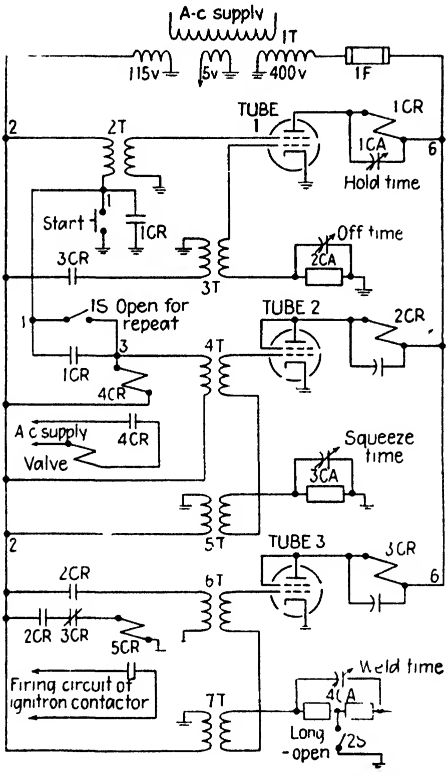


FIG. 12C.—Weltronic sequence weld timer

reset. If switch $1S$ is open for a repeat weld and the starting switch is held closed, the opening of $1CR$ contact 1-to-3 at the end of the first weld separates the electrodes by dropping out $4CR$; $1CR$ also opens the circuit to $4T$, permitting $3CA$ to recharge and turn off tube 2, dropping out $2CR$. Similarly, the $2CR$ contact shuts off $6T$ and tube 3, dropping out $3CR$. The $3CR$ contact (near the starting switch) removes the voltage of transformer $3T$, but tube 1 is still kept from firing again by the

negative grid voltage remaining across $2CA$. Tube 1 will fire again as soon as $2CA$ has discharged, measuring the off time. Tube 1 then picks up relay $1CR$ again; $4CR$ and the solenoid valve bring the electrodes onto the work to make another weld. Notice that the grid circuit of tube 1 measures the off time, while the anode circuit of the same tube measures the hold time. A change of either time setting will not affect the other time.

12-10. D.C. and A.C. Combined in a Weld Timer (CR7503-F178).—The sequence weld timer shown in Fig. 12*D* is of later design than that described in Sec. 12-3. The elementary diagram, Fig. 12*E*, shows that a regulated d-c supply is used for the thyratron grid circuits, while the tube anodes and the relay coils operate on a.c., supplied by transformer $1T$ at the right-hand side.

At the left-hand side of Fig. 12*E*, another secondary winding of transformer $1T$ furnishes an a-c voltage, which is rectified by tube 7 and filtered[10-4] by $1R$ and capacitor $1C$ By means of voltage-regulator[10-6] tube 8 (and its buffer resistor $2R$) a steady d-c supply of 150 volts is held between the positive point 75 and negative point 70. Resistors $3R$ and $4R$ divide this 150-volt supply so that point 70 is always 90 volts more negative than 10, which is connected to the cathodes of the thyratron tubes 1, 4, 5 and 6. About a minute after the a-c supply is connected to $1T$, all tubes are ready to operate; tube 8 is glowing.

Before the starting switch is closed (right-hand side of Fig. 12*E*), no thyratron can pass anode current and no relay is picked up, for point 10 (thyratron cathodes) is not connected to transformer $1T$. Let us begin with switch $3S$ open, to give a single (nonrepeat) welding operation; $3S$ keeps relay $6TD$ from operating.

Notice that the circuits near tube 1 (which control the squeeze time) are the same as the circuits near each of the other thyratrons; only one tube circuit needs to be explained.

The grid of tube 1 is connected, through $14R$ and the closed $1CR$ contact, to 70; since point 70 is 90 volts more negative than the tube-1 cathode 10, tube 1 has a grid voltage of -90 volts. Through this closed $1CR$ contact, 150 volts d.c. is connected across resistors $11R$ and $12R$; capacitor $11C$ is charged to this same voltage.

When the starting switch closes, it picks up relay $1CR$; one

1*CR* contact near the starting switch keeps 1*CR* energized. Another 1*CR* contact picks up the solenoid valve (lower right) to bring the electrodes onto the work. (Tubes 1, 4 and 5 now have

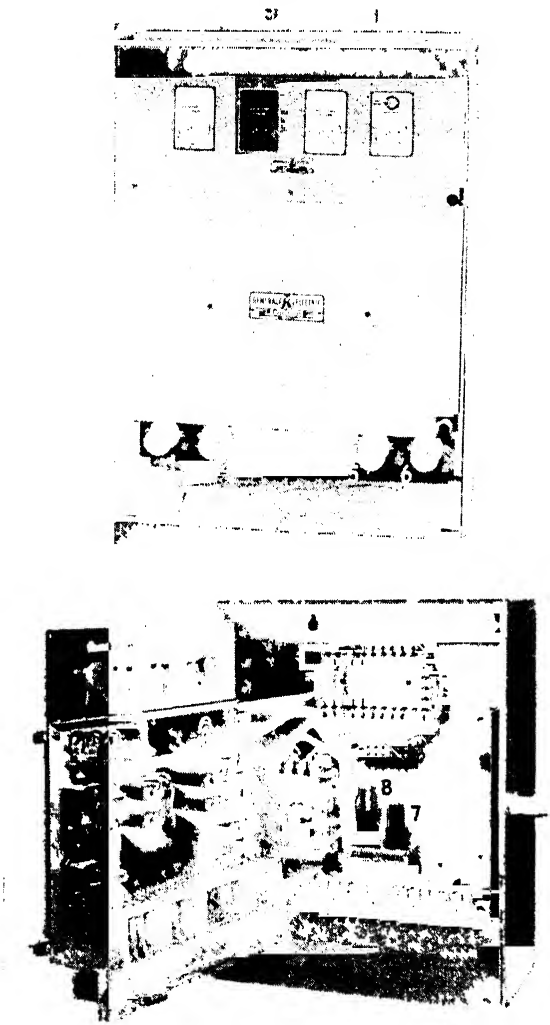


FIG. 12*D*.—Photograph of sequence weld timer (CR7503-F178).

a-c voltage between the anode and the cathode, but they are kept from firing by their grids.) Another 1*CR* contact opens below tube 1, disconnecting point 15 from point 70. The poten-

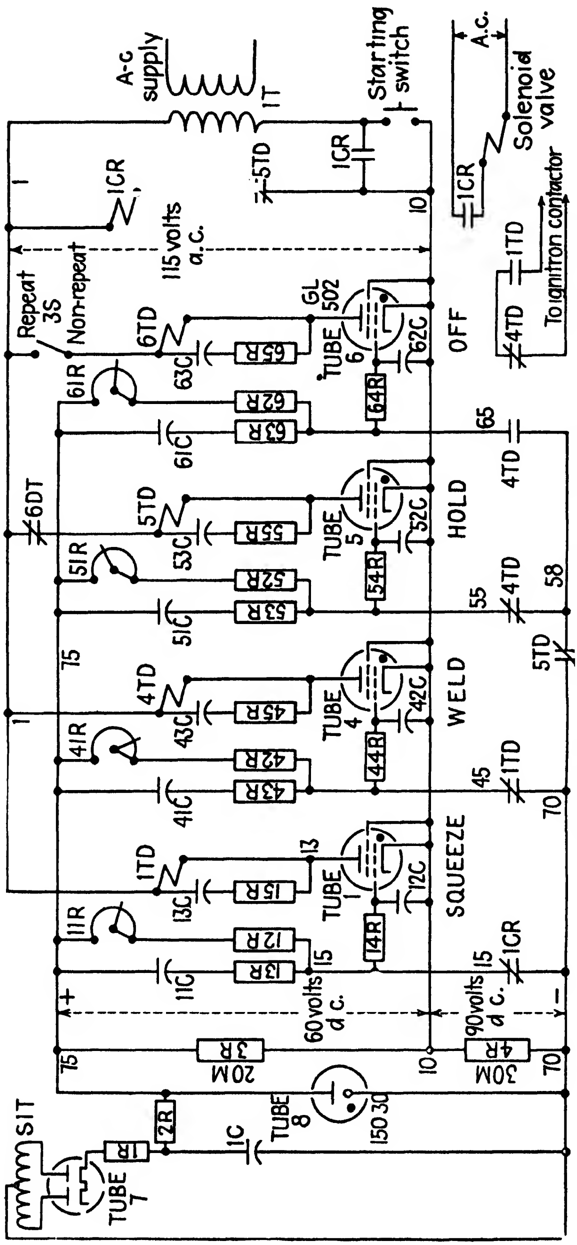


FIG 12E.—Diagram of sequence weld timer (CR7503-F178)

tial of point 15 (grid of tube 1.) now rises slowly, as capacitor $11C$ discharges through the combined resistance of $11R$, $12R$ and $13R$. Even if $11R$ is turned so that all its resistance is shorted, about 2 cycles of time pass before the voltage across $11C$ has decreased to about 60 volts, to let point 15 (grid) be near the same potential as 10 (cathode), so that tube 1 can fire. This time delay (before tube 1 fires) is the squeeze time; to increase this delay, more of the $11R$ resistance is put into circuit, so that $11C$ discharges more slowly.

Tube 1 picks up relay $1TD$, to start the weld time; one contact of $1TD$ closes the ignitor circuit (lower right in Fig. 12*E*) so that welding current flows. Another $1TD$ contact (below tube 4) opens and lets the potential of point 45 (grid of tube 4) rise, as capacitor $41C$ gradually discharges at a rate set by $41R$.

At the end of the weld time, tube 4 picks up relay $4TD$; one $4TD$ contact opens the ignitor circuit and stops the welding current. Another $4TD$ contact opens below tube 5, letting the potential of point 55 rise as $51C$ discharges at a rate set by $51R$. After the hold time, when tube 5 picks up relay $5TD$, the $5TD$ contact opens (above the starting switch), letting $1CR$ drop out. Even if the starting switch is held closed, the $1CR$ contact (70-to-15) turns off* tube 1; the $1TD$ contact (70-to-45) turns off tube 4. However, tube 5 continues to pass current (since its contact 70-to-58 remains open); after the starting switch is released, the next welding operation may be started.

If $3S$ is closed, for repeat welding, tube 6 passes current as soon as the starting switch closes. However, after the weld time, relay $4TD$ closes its contact 58-to-65; this makes the grid 65 of tube 6 negative, so that tube 6 drops out relay $6TD$. Capacitor $61C$ becomes charged. After the hold time, relay $5TD$ opens its contact 70-to-58, so that the potential of grid 65 rises as capacitor $61C$ discharges through $61R$, measuring the off time. When tube 6 fires (and the starting switch is yet closed), the $6TD$ relay opens its contact (upper center of Fig. 12*E*), which drops out $5TD$. The $5TD$ n-c contact recloses, above the starting switch, picking up $1CR$ to begin another welding operation.

12-11. Synchronous Timing.—Although the weld timers just described may control the flow of welding current for times as short as two or three cycles, greater accuracy is needed for weld-

* Since a-c anode voltage is used, each thyratron is prevented from further firing after its grid is connected to the negative potential of point 70

ing certain metals and for producing the same amount of heat in each spot weld. To get these results, an a-c welder must be controlled by tube circuits that can start the flow of welding current always at the same point in the 60-cycle voltage wave. Figure 12*F* shows this voltage wave and pictures the current that flows if the weld is started at points *W*, *X*, or *U*. Since a welding transformer is a lagging-power-factor load, the welder tries to draw current that lags (starting at *X*) behind the voltage; if the welding current begins to flow at *X*, its waveshape remains

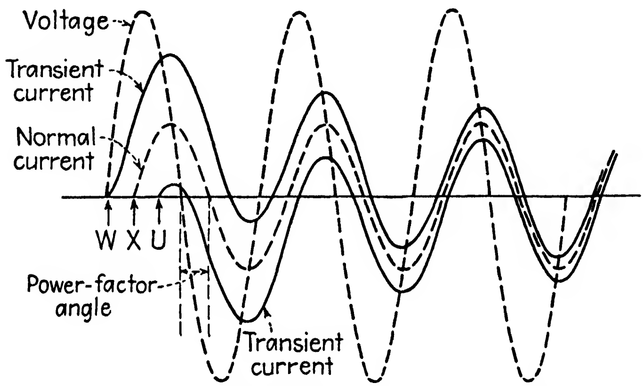


FIG. 12*F*.—Transient currents (starting before or after the power-factor angle).

the same, one cycle after another, and gives the best a-c weld. However, if the contactor closes the welding circuit at *W* (perhaps only 1⁄1000 sec. earlier than *X*), the amount of current rises much higher than before; for three or four cycles this current is "off balance" before it returns to normal. This short-time disturbance is called a *transient current*. Similarly, if it is started late at *U*, the current again is much greater (below the 0 line). Whether started early or late, this increased current changes the amount of heat during that weld. So, especially when the welding current flows for less than five cycles, far better welds are made when tube-operated circuits start the flow of current always at point *X*. Such accurate starting of the welds, always exactly in step with the a-c voltage wave, is called *synchronous timing*.

While many kinds of synchronous-control equipment are described elsewhere,* Fig. 12*G* shows another control as an

* CHUTE, G. M., "Electronic Control of Resistance Welding," McGraw-Hill Book Company, Inc., New York, 1943.

example of a synchronous timer; its circuit appears in Fig. 12*H*. In Fig. 12*H* we shall see that tube 5 starts the flow of welding current always at the same point in the voltage wave. Similarly, the heat-control circuits of Chap. 13 also start the current to flow at carefully controlled points on the voltage wave.

Most synchronous spot-welding timers include a circuit that lets the welding current flow for 1, or 2, or 10 cycles, or other lengths of time, as selected by turning a dial. These timers also make sure that each weld includes an even number of half cycles of current flow—that is, the current flows for 2 or 5 com-

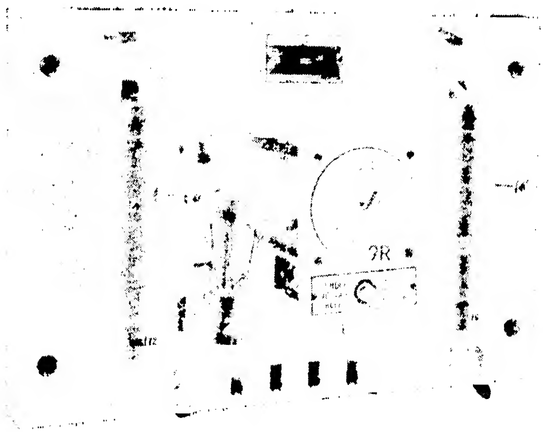


FIG. 12*G* Synchronous control for a small spot welder (CR7503-A138).

plete cycles, but not for 1½ or 4½ cycles. If the weld starts with a positive half cycle, it always ends with the opposite, or negative, half cycle. In this way, a new weld never starts with the same kind of half cycle that ended the previous weld. This is important where only part of a second separates the welds; the magnetism left in the welding transformer has not yet drained away, so it affects the current and the heat of the next weld, unless the current starts in the right direction. As shown in Fig. 12*H*, tubes 5 and 6 are connected back to back,[9-5] to permit alternating current to flow to the welding transformer. Tube 5 always is the first to pass current—tube 6 always is the last to pass current. The part of the synchronous timer that causes this action is called the *leading-tube—trailing-tube circuit.*[12-16]

12-12. Synchronous Control for Small Welders (CR7503-A138).—For welders needing less than 50 amperes from the a-c supply line, a pair of thyratrons may be used instead of ignitrons to switch this current flow. In Figs. 12*G* and 12*H*, thyratron tubes 5 and 6 are used in this way. When not welding, thyratron tube 2 fires steadily, thereby preventing tube 5 from firing.

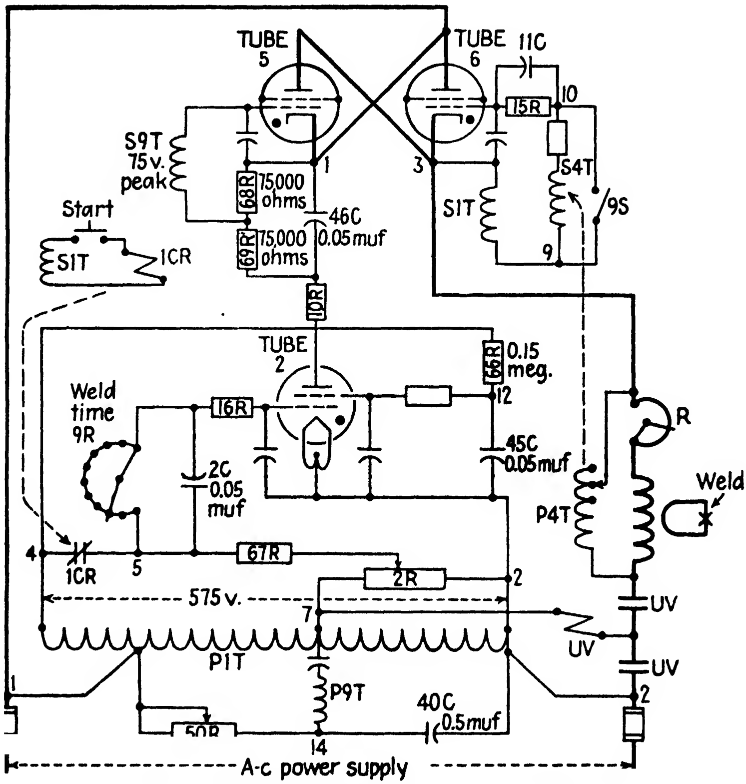


FIG. 12*H*.—Circuit of synchronous control (CR7503-A138).

When the starting switch closes, tube 2 stops firing and lets tube 5 pass current, which in turn fires tube 6. Tubes 5 and 6 are all-metal shield-grid thyratrons (see Fig. 11*L*).

The a-c power enters at the bottom of Fig. 12*H*; the main current flows only through the welding transformer and its heat-adjusting resistance *R*, and through tubes 5 and 6 to the other side of the power supply. The a-c supply also connects to transformer 1*T* whose primary taps furnish 230, 460 and 575 volts to

the various control circuits. Secondary windings $S1T$ give 115 volts, where shown, and also heat the tube filaments. After heating the tubes 5 min, relay UV may be pushed in to make ready to weld. The UV coil is held closed through its own contact; if supply voltage fails, UV drops out, giving undervoltage protection.

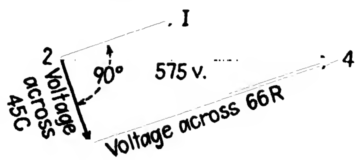
Notice that Fig. 12H has no rectifier tube 1 to furnish a d-c supply, often included in synchronous controls. Instead, the timing capacitor $2C$ (near tube 2) is charged through tube 2, as shown below. Tube 2 is controlled by two signals, one applied to the control grid, the other signal at the shield grid.[11-10]

While the starting switch is open, relay $1CR$ is not energized, so its n-c contacts are closed (at lower left in Fig. 12H), and there is a drop of 575 volts between points 5 and 2. During the half cycle when 5 is more positive than 2, electrons flow from 2, cathode to control grid of tube 2, through $16R$ and $9R$ to 5. Nearly the whole 575 volts is across $9R$ and charges $2C$ to the crest[5-6] of this voltage (shown at C in Fig. 12I). During the following half cycle, electrons cannot flow grid to cathode, so $2C$ holds its charge because of this grid rectification;[5-4] part of the $2C$ voltage leaks off through $9R$, but $2C$ is recharged once each cycle, while the $1CR$ contact remains closed.

12-13. Control by Shield Grid.—In Fig. 12H, the shield grid of tube 2 prevents all current flow in tube 2 (including this control-grid current for recharging $2C$) until a point near the middle of the anode-voltage wave, shown at point A in Fig. 12I.* Halfway down in Fig. 12I, notice the sine wave of voltage applied to the shield grid of tube 2; this voltage lags about 70 deg behind the anode voltage, because of capacitor $45C$ and resistor $66R$.†

* BIVENS, M. E., Special Welding Controls, *Electronics*, October, 1942.

† As explained in Sec. 13-5, this connection of $45C$ and $66R$ across 575 volts (points 2 to 4) may be shown by the vector triangle. Current I, flowing through 150,000 ohms and $45C$ (which represents $1{,}000{,}000/2\pi fC$ (mu f) or 53,000 ohms at 60 cycles) is seen to lead the 2-to-4 voltage by less than 20 deg. The size of the voltage across $45C$ (which is also the shield-grid voltage of tube 2 and lags 90 deg behind current I), is seen to be about $\frac{1}{3}$ as large as the 2-to-4 voltage. Since this 2-to-4 voltage is in phase with the anode voltage of tube 2, the $45C$ shield-grid voltage lags perhaps 75 deg behind the anode voltage.



Notice that the shield grid remains negative early in the half cycle of anode voltage, but crosses the zero line at point A. Ahead of point *A*, the shield grid is so negative that it prevents

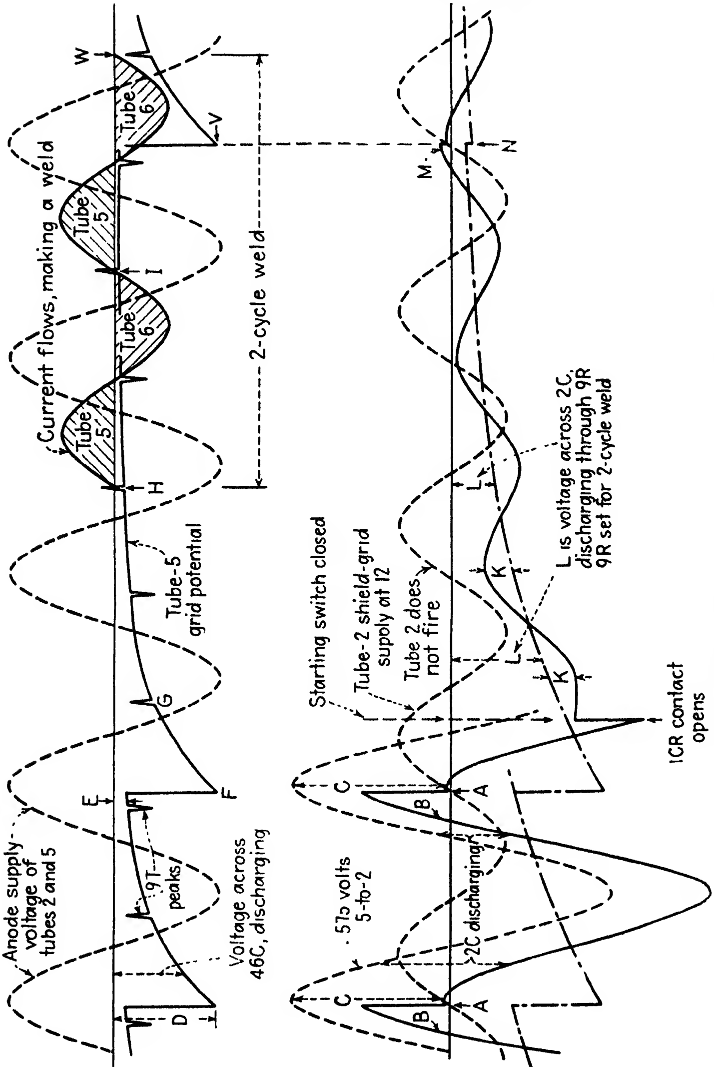


FIG. 12*I*.—Waveshapes in timing circuit of Fig. 12*H*.

the flow of anode current, even though the tube-2 control grid has already become positive at *B*. When the shield grid swings positive, at *A*, it permits electrons to flow, cathode to control

grid, recharging $2C$; at this same instant, the electrons flow *cathode to anode in tube 2, through 10R, 69R and 68R to point 1. In this circuit, most of the* a-c *supply voltage* appears across $68R$ and $69R$, charging capacitor $46C$ to the crest[5-6] of this voltage. As shown at D in Fig. 12I, this voltage across $68R$ keeps the grid of tube 5 quite negative; the negative end of $68R$ is connected to tube-5 grid, through $9T$. Transformer $9T$ is a peaking transformer, a nonelectronic device explained in Sec. 28-5. Transformer $9T$ produces no voltage most of the time, but gives two sharp peaks of voltage during each cycle; one of these voltage peaks is used for firing tube 5 later at point H.

Although $46C$ discharges quite rapidly through $68R$ and $69R$ (so that the control grid of tube 5 may become only 50 volts negative, as shown at E in Fig. 12I), $46C$ is recharged by the firing of tube 2; this lowers the tube-5 grid potential to F before the next positive voltage peak G from $9T$ can fire tube 5. So, until the starting switch is closed, tube 2 passes current once each cycle; its anode current recharges $46C$ to keep tube 5 from firing, while its control-grid current recharges $2C$ so that $2C$ is always ready to control the weld time, as next described. Meanwhile, tube 6 cannot fire, as described in Sec. 12-16.

12-14. Synchronous Action, Making the Weld.—The electrodes press onto the work metal before the starting switch is closed. To let current flow to make a weld, relay $1CR$ opens its contact (in Fig. 12H). This disconnects point 5 from the 575 volts at point 4, so the grid of tube 2 is not driven positive again. Instead, the tube-2 grid is kept negative by the voltage or charge of capacitor $2C$. (Point 5 drops to the same potential as the slider on $2R$; the a-c voltage of slider-to-2 appears at K in Fig. 12I.) Since tube 2 cannot fire, its anode current fails to recharge capacitor $46C$; as the voltage across $68R$ continues to decrease, the next positive $9T$ peak reaches up and fires tube 5 at H and again at I. Because tube 5 fires, tube 6 also passes current during its own half cycle, as explained in Sec. 12-16; we see that welding current flows for two complete cycles.

This is a two-cycle weld because the resistor dial $9R$ is set at the two-cycle position. So set, most of $9R$ is shorted; capacitor $2C$ must discharge through the unshorted portion of $9R$. Meanwhile, the negative control grid keeps tube 2 from firing, even though its shield-grid voltage rises as before. At L in Fig. 12I,

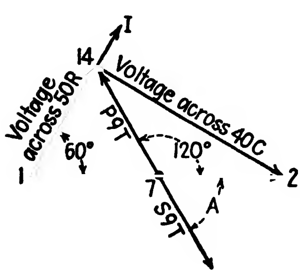
we see the voltage across $2C$ decreasing (at a rate depending on the setting of $9R$); at M the a-c voltage again has driven the control grid of tube 2 positive, so that the shield-grid voltage again fires tube 2, at N. The anode current of tube 2 quickly recharges capacitor $46C$, lowering the tube-5 grid potential at V; this again prevents the $9T$ peaks from firing tube 5. At W tube 5 cannot start another cycle of current flow, so the weld is ended.

12-15. Using a Peaking Transformer.—As described in Sec. 28-5, a peaking transformer has windings like an ordinary transformer. However, although the input may be a sine wave, there is so little iron in its core that the output is a sharp voltage peak.

Such a peaked voltage is important in grid circuits of welding-control thyratrons. Since the peak lasts for only 5 or 10 degrees (compared with 180 degrees for half of a sine wave), this peaking transformer will not fire a thyratron at any point earlier or later than the desired point on the voltage wave.

To adjust or choose the point where the voltage peak occurs, it is necessary to shift the a-c voltage applied to the primary of this peaking transformer. The primary winding is shown at $P9T$, near the bottom of Fig. $12H$. By moving the slider on resistor $50R$ to decrease the resistance,* we are able to make the voltage peak appear earlier in the half cycle of tube-5 anode voltage. By this adjustment, the welding current is made to start always at the power-factor angle of the welding transformer—the point where the current wave most naturally crosses the zero line.

* As explained in Sec. 13-5, this connection of $50R$ and $40C$ (across the 460 volts of the $P1T$ transformer winding 1-to-2) may be shown by a vector triangle. If the slider is moved until all but 2600 ohms of $50R$ is shorted, the current I leads the 1-to-2 voltage by 60 degrees. (The 0.5 mu f capacitor $40C$ represents $1{,}000{,}000/2\pi fC$(mu f) or 5320 ohms at 60 cycles.) The primary $P9T$ receives the voltage that is between points 7 (mid-point of the 1-to-2 winding) and point 14 (where $50R$ and $40C$ join); this voltage is seen to lead the 1-to-2 voltage by 120 degrees. By the reversal of the secondary leads, the voltage peak of $S9T$ is made to occur about 60 degrees (angle A) behind the 1-to-2 voltage. If the slider is moved so that more of $50R$ resistance is in circuit, the length of vector 1-to-14 increases, and A increases; the $S9T$ peak fires tube 5 later in the half cycle.



12-16. Leading-tube—Trailing-tube Action.—While the starting switch is open and tube 5 is not passing current, tube 6 in Fig. 12*H* is prevented from firing, because of the a-c voltage of transformer *S1T* in its grid circuit. As shown in Fig. 12*J*, this *S1T* voltage is exactly out of phase with the anode voltage of tube 6, so the *S1T* terminal 9 is more negative during the half cycle when

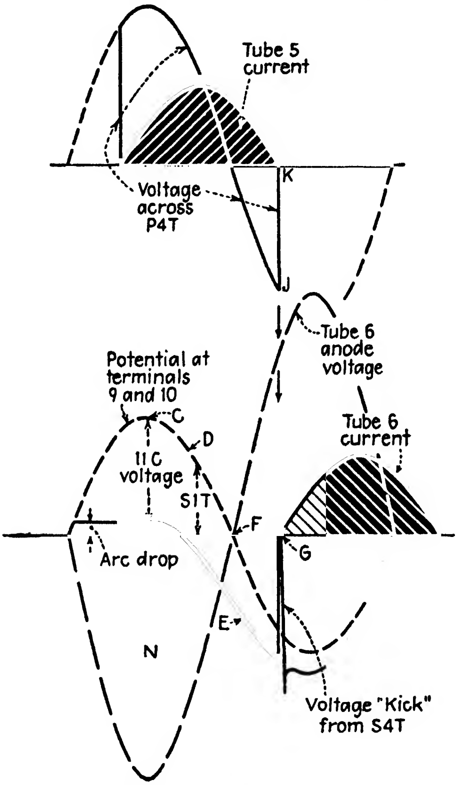


FIG. 12*J*.—Waveshapes in leading-tube–trailing-tube circuit.

tube-6 anode is positive; this terminal-9 negative potential keeps tube-6 grid negative and prevents tube 6 from firing. During the half cycle (*N* in Fig. 12*J*) when tube-6 anode is negative, terminal 9 of *S1T* becomes more positive (shown at *C*). If this high positive voltage reaches the grid, tube 6 may be damaged; resistor 15*R* takes most of this voltage and lets the grid become only 15 volts positive, due to the arc drop. Capacitor 11*C*, connected across 15*R*, becomes charged by the grid current as shown

in Fig. 12*J*. When the *S1T* voltage decreases, the potential at point 10 also decreases, as shown at *D*. Since 11*C* cannot lose this charge quickly, this 11*C* voltage forces the tube-6 grid more negative than point 10, as shown at *E*. In this way, accidental firing of tube 6, at point *F*, is prevented.

Now we come to the circuit that fires tube 6 only if tube 5 has passed current during the half cycle before. In Fig. 12*H*, notice the transformer whose primary *P4T* is connected across the welding transformer; its other winding *S4T* is in the grid circuit of tube 6. When tube 5 fires and applies voltage across the welding transformer, this same voltage reaches *P4T*. The waveshape of this voltage appears in the upper part of Fig. 12*J*. Just before the current of tube 5 stops, the voltage across *P4T* is quite large, as shown *J*-to-*K*. When the tube-5 current stops, the voltage across *P4T* suddenly decreases to zero. This sudden change of primary voltage causes *S4T* to give a large voltage "kick." This positive *S4T* voltage is larger than the negative voltage of *S1T*, and fires tube 6 at *G*. Current then flows through tube 6, so as to complete the full cycle started by tube 5. If tube 5 has not been passing current, *S4T* gives no voltage "kick" and tube 6 is not fired.

To give a weld only ½ cycle long, switch 9*S* is closed in Fig. 12*H*, preventing the *S4T* "kick" from firing tube 6. Switch 9*S* is combined with the weld-time adjuster 9*R*; in the ½-cycle position, 9*S* closes but the resistance of 9*R* is the same as for a 1-cycle weld. Tube 5 passes all the welding current.

Although the sequence weld timers (Secs. 12-3 to 12-10) are welding controls, they mainly operate the sequence or mechanical action of the welding machine; they give no synchronous timing. In Fig. 12*H*, this example of synchronous control lets welding current start to flow only at one point on the voltage wave, when the peaking transformer *S9T* fires tube 5. Welding current is started always by tube 5; as tube 5 stops, tube 6 fires, so that the weld ends with current flowing opposite to its starting current. The time length of the current flow is accurately controlled by the combination of 9*R* and 2*C*.

For a small welder, the welding heat (amount of welding current) may be controlled by a series resistance (*R* in Fig. 12*H*). For larger welders, this change of heat is obtained by phase-shifting the thyratrons, as described in Chap. 13.

12-17. Welding with a Half Cycle. CR7503-A136.—A small welder sometimes gives best results if its transformer receives a current impulse of perhaps several hundred amperes, lasting about a half cycle or about $\frac{1}{100}$ sec. The circuit of Fig. 12*K* uses a small ignitron tube 3 to permit this current to flow; for each weld, tube 2 fires ignitron 3 only once, so that welding current flows during that half cycle only.

In Fig. 12*K*, tube 1 rectifies to produce a d-c voltage between points 4 and 6, which voltage is filtered by reactor 2*X* and capaci-

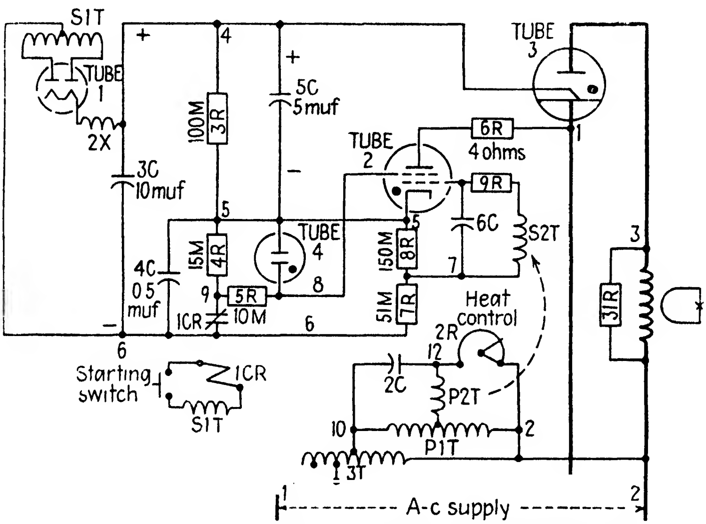


FIG. 12*K*.—Circuit of half-cycle welder control (CR7503-A136).

tor 3*C*. Until the starting switch closes, contact 1*CR* remains closed, so direct current flows through resistors 3*R** and 4*R* as a voltage divider. Most of this 4-to-6 voltage appears across 3*R*, and the large capacitor 5*C* charges to this voltage; (later, 5*C* will discharge, to fire ignitron 3). Notice that the cathode of thyratron tube 2 is connected at 5, between 5*C* and 4*R*; the voltage across 4*R* (while 1*CR* contact is yet closed) keeps the shield grid 8 about 60 volts negative. Meanwhile, the control grid of tube 2 is kept about 45 volts negative (at point 7 on the 7*R*-8*R* divider); the voltage of the peaking-transformer secondary

* The 100M, shown next to resistor 3*R* in Fig. 12*K*, stands for 100,000 ohms; M is used in many diagrams to stand for 1000. Other diagrams use K to stand for 1000, so that 15K means 15000 ohms.

S2T forces the control grid positive once during each cycle of the a-c supply voltage. (This positive peak occurs during that half cycle when the anode of ignitron 3 is positive.) However, this peak does not yet fire tube 2, while its shield grid is 60 volts negative. These conditions are pictured at *A* in Fig. 12*L*.

When the starting switch picks up 1*CR* in Fig. 12*K*, the 1*CR* contact disconnects point 9 so that the shield grid 8 loses its 60-volt negative bias. (Capacitor 4*C* helps to prevent any change in cathode-5 potential.) The shield grid no longer prevents

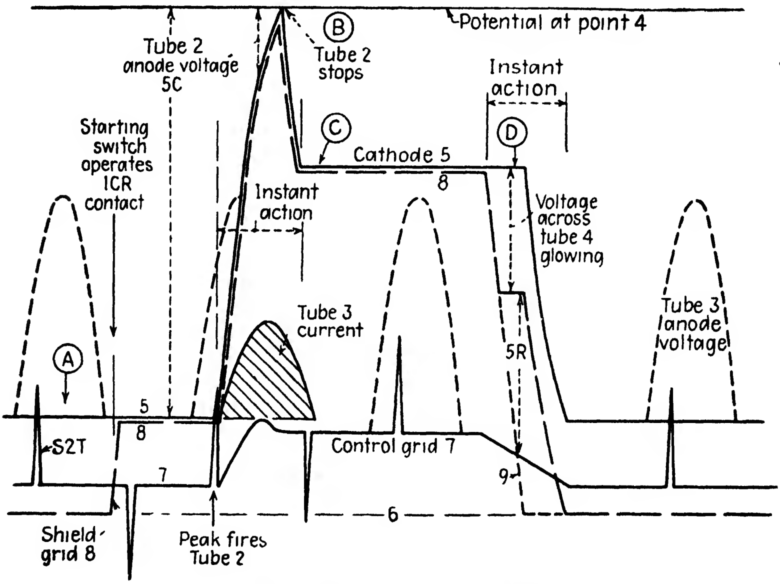


FIG. 12*L*.—Circuit action in Fig. 12*K*.

tube 2 from firing, so the next positive peak of *S2T* fires tube 2. Capacitor 5*C* quickly discharges, forcing electrons to flow from cathode to anode of tube 2, through 6*R*, from pool cathode to ignitor of tube 3; this sudden current fires ignitron 3, so that anode current flows through tube 3 and the welding transformer, making the half-cycle weld. When tube 2 fires and discharges 5*C*, notice how the potentials of points 5, 7 and 8 change instantly in Fig. 12*L*. The tube-2 cathode 5 rises until the anode-to-cathode voltage is too small at *B* to cause more flow of anode current; the tube-2 control grid immediately gains control, preventing any further firing of tube 2. Cathode 5 drops to a potential

at C, which depends on the voltage-divider action of $3R$, $8R$ and $7R$; at this potential, cathode 5 is far above the peaks of $S2T$, so tube 2 cannot fire a second time.

Later, when the starting contact is released and $1CR$ contact closes, point 9 quickly drops to the negative potential of point 6; for just an instant (at D in Fig. 12L) the tube-2 shield grid could be several hundred volts more negative than cathode 5, but this is prevented by tube 4. This neon glow tube[10-7] 4 acts as a voltage-regulator tube, so that it holds only about 70 volts across its terminals; any excess voltage appears across $5R$. In this way, the tube-2 shield grid becomes no more than 70 volts negative.

The $S2T$ voltage peak gives synchronous control of the welder; this peak starts tube 3 to pass current, always at the same point in the a-c voltage wave. By turning the heat-control dial ($2R$, lower right in Fig. 12K) to decrease its resistance, the $S2T$ peak may be made to occur earlier in the half cycle, so that tube 3 passes current for a larger part of the cycle, causing a hotter weld. This $2R$ adjustment* shifts the a-c voltage applied to the peaking-transformer primary $P2T$; this is called phase-shift heat control, as explained in the next chapter.

Questions

True or false? Explain why.

1. A 5-min time-delay relay is needed to protect the tubes in all welding controls.

2. No point in a tube circuit may be below ground potential.

3. It is possible to make good welds with current that flows for $1\frac{1}{2}$ or $2\frac{1}{2}$ cycles, even if one weld is made soon after another weld.

4. Thyratrons give more accurate control of welding than big ignitrons can give.

5. If a shield-grid thyratron is used in place of tube 1 in Fig. 12C, it fires before the start switch closes.

6. A.c. and d.c. cannot be used in the same circuit.

7. All circuits (in Chap. 12) that set the length of weld time, depend on the RC time constant.

8. Any welding control is synchronous if it carefully counts the number of cycles while welding current flows.

9. A dip in supply voltage while welding current flows affects the time-delay actions in Fig. 12H.

10. Grid rectification (flow of grid current to charge a capacitor) is used (a) in Fig. 12H. (b) in Fig. 12K.

* This circuit of $2R$, $2C$ and $P2T$ appears again in Fig. 13R and is described in Sec. 13-14.

11. Suppose that two timers are used together, so that the $2CR$ contact ($8A$-to-$8B$ of Fig. 12B) becomes the "Start" switch of Fig. 12H. If $4TD$ (of Fig. 12B) is set for 5 cycles, and $9R$ (of Fig. 12H) is set for 10 cycles, for how many cycles does the welding current flow?

12. If tube 3 of Fig. 12C is removed, what happens after the "Start" switch closes?

13. In Fig. 12E, if $12R$ and $13R$ total 30,000 ohms, how large is capacitor $11C$? (The shortest squeeze time is 2 cycles.)

14. In Fig. 12E, is capacitor $12C$ (near tube 1) more likely to be 1 mu f or 0.001 mu f? Why?

15. In Fig. 12K, if capacitor $6C$ is shorted, how does this affect the welding results?

CHAPTER 13

GRADUAL CONTROL OF THYRATRONS BY PHASE SHIFTING

Previous chapters have shown how the vacuum tube can gradually change the amount of its anode current in response to a gradual change in the signal voltage applied to the grids. We have also seen that very large currents (compared to currents carried by vacuum tubes) can be turned on and off by using thyratrons or ignitrons. At the same time, we have had to realize that the amount of current flowing through such vapor-filled tubes is limited only by the load circuit, just as the amount of amperes flowing through the tips of a magnetic contactor depends on the load supplied by the contactor. With a magnetic contactor, the coil can close the contact tips, but cannot control the amount of current flowing through the tips. In the same way, the thyratron grid and ignitron ignitor can turn on or fire these tubes when desired, but cannot control or limit the amount of anode current flowing, once the tubes have fired.

13-1. Varying Power Through Gas-filled Tubes.—Fortunately, there are ways by which we can control thyratrons and ignitrons so that they will change or limit the average current flowing through them. Such methods are usually known as phase-shift controls. A phase-shift circuit is used in a welding heat-control unit (Fig. 13*J*) designed for use with an ignitron contactor to control the amount of current through the primary of a welding transformer. The secondary of this welding transformer supplies current to the welder electrodes and in turn produces heat at the junction of the metals being welded. By using this heat control, it is possible to change quickly and accurately the amount of weld current and thereby control the weld heat.

Before introducing the heat-control circuit, let us proceed through several basic steps: (1) see how a thyratron tube is often used to control an ignitron; (2) apply an alternating-

current grid voltage to control the thyratron; (3) study methods for changing the phase of this a-c grid voltage; and (4) watch the resulting waveshapes when two such thyratrons are connected to an inductive load.

In (*a*) of Fig. 13*A*, we close a single-pole switch *S* to connect voltage to the starter of an ignitron, so that as much as 40 amperes can flow into the ignitor to fire this big tube. (A rectifier is in series with the ignitor to prevent the flow of reverse current, which would ruin the ignitor.[9-9]) In place of this switch, a thyratron tube is often used, as shown in (*b*) of Fig. 13*A*. Since the thyratron is connected in series with the ignitor or starter, the ignitron cannot fire until the thyratron first passes a "slug" of current into the ignitor. Therefore, whatever grid potential controls the thyratron (turns it on or off in an a-c circuit) this same grid potential in turn controls the firing of the ignitron. With this combination of a thyratron and an ignitron, a large amount of current (perhaps thousands of amperes) can be controlled by small changes in the grid voltage supplied at *A* (measured between grid and cathode of the thyratron). This shows that an ignitron is easily controlled by a thyratron; we may now center our attention on the thyratron alone.

13-2. The Thyratron A-c Grid Circuit.—In (*c*) of Fig. 13*A*, we find a single thyratron whose grid circuit includes a transformer 2*T* which supplies a 60-cycle sine wave of grid voltage at *A*. By changing transformer connections, we can make this a-c voltage be exactly in phase with the a-c anode voltage of the thyratron, or be 180 degrees out of phase. (As we shall explain later, it is possible to get *any* phase relation between these extremes by means of an added circuit.)

If transformer 2*T* is so connected that the tube grid becomes more positive at the same instant that the anode becomes positive, the tube will fire at the beginning of every positive half cycle. As shown in (*a*) of Fig. 13*B*, the grid is never negative at the right time to keep the tube from firing; that is, the grid and anode voltages are in phase. (In all such diagrams, remember that the cathode potential is represented by the zero line. No critical-grid-voltage wave is shown. See Sec. 11-5, footnote.) At the very beginning of the half cycle, the grid potential is more positive than the cathode, and the tube fires at point

D, where the grid potential crosses the zero line. The tube passes current during the entire half cycle.

Let us now interchange terminals 1 and 2 of transformer 2*T*. The grid potential now becomes more negative while the anode potential is increasing in a positive direction, as shown in (*b*) of Fig. 13*B*. This shows that the grid voltage is 180 degrees out of phase with the anode voltage. In (*b*) while the anode is positive the grid is always more negative than the zero line, and so the tube never fires. (Although the grid potential

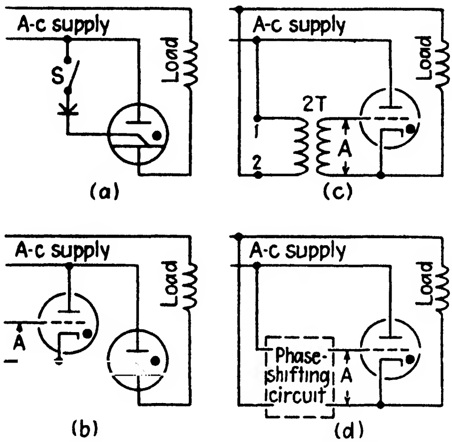


FIG. 13*A*.—Ignition fired by a thyratron, whose grid voltage may be phase-shifted

becomes positive during the half cycle *X*, the tube anode is then more negative than the cathode, and the tube cannot fire.)

13-3. Shifting the Thyratron-grid Phase.—We must learn what happens in the tube when the a-c grid voltage is at some other phase angle than in the two cases mentioned. In Fig. 13*A*, (*d*) shows the same circuit as (*c*), except that the dotted rectangle contains a "phase-shifting circuit." As described later, this circuit can make the a-c grid-voltage curve either lag or lead the curve of anode voltage. By "lag" we mean that the grid-voltage curve does not cross the zero line and become positive until after the anode voltage has become positive. The term "lead" means just the opposite; that is, the grid voltage becomes positive before the anode voltage. If the grid crosses the zero line (in an upward or positive direction) one-fourth cycle later than the anode voltage, we say that the

grid voltage lags the anode voltage by 90 degrees. (One complete cycle is 360 degrees, including one positive half cycle and one negative half cycle.)

If we now adjust the phase-shifting circuit of (*d*) so that the grid voltage leads the anode voltage by some angle *Y*, the resulting conditions are shown in (*c*) of Fig. 13*B*. When the anode

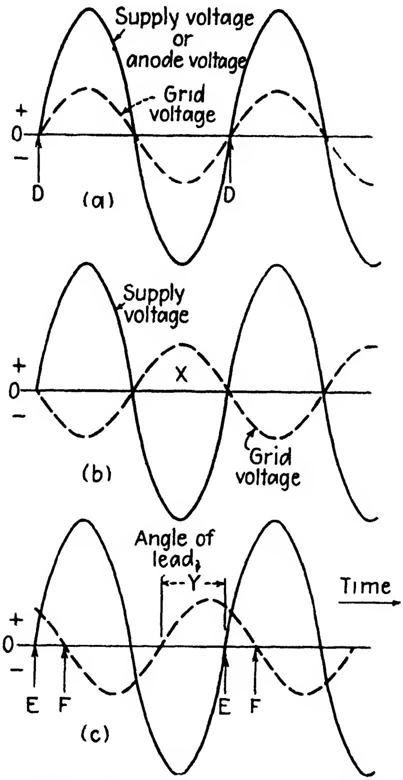


FIG. 13*B*.—Waveshapes of anode voltage and grid voltage.

becomes positive, the grid is already positive, so the tube fires at *E*. Even though the grid potential becomes more negative or below the zero line, as shown at *F*, it has no effect on this vapor-filled tube, since it is already passing anode current. The tube passes current during the entire half cycle and all the following half cycles when the anode is positive.

Now let the grid voltage lag the anode voltage and see what

happens. As is shown in (*a*) of Fig. 13*C*, the grid-voltage curve now lags the anode voltage by a small angle *Z*. As the anode becomes positive, the grid is still negative, as shown at *A*; the tube does not pass current. However, the grid voltage does not stay negative, but increases in a positive direction. Just as soon as the grid voltage rises above the zero line, as shown at *G*, the tube fires. Once the tube has fired it makes no difference what the grid potential is during the rest of the half cycle. Here we make the tube pass current for less than a half cycle;

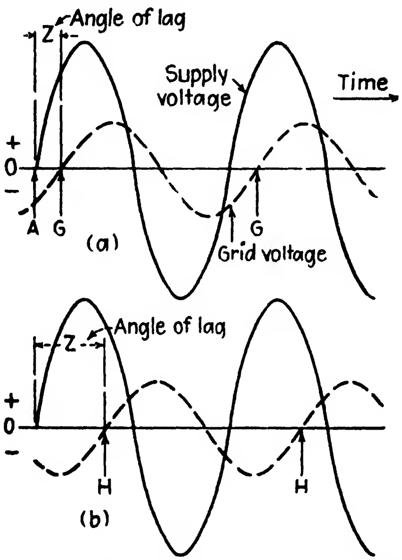


FIG. 13*C*.—Lagging grid-voltage waves for delayed firing.

in (*a*) the tube conducts for about three-fourths of its entire half cycle.

Figure 13*C* shows the same conditions at (*b*) as at (*a*), except that the grid voltage lags by a greater angle, so that the tube fires much later in the half cycle (as shown at *H*); current flows for a smaller portion of each half cycle.

13-4. Steam On and Off to Control the Heat.—The phase-shift control of thyratrons just described, is like a steam-heating system that has no regulating valve; its ordinary valve can turn the steam full on or can shut off the steam completely. Yet we want medium amounts of steam, to give us less heat on a mild winter day than on a very cold day.

This need is met by adding a "cycling" device, which shuts off the steam valve every 30 minutes, at each point A in Fig. 13D. Then a thermostat is added, which controls only the turning on of the steam. During a cold wave, when the steam is shut off at A, the thermostat immediately reopens the valve so that the steam is always available. On an ordinary winter morning, there is enough heat if the valve stays shut 5 min before opening at B in Fig. 13D. By 10 A.M. it is warmer outdoors, so the thermostat keeps the valve shut about 15 min (or one-half of each 30-min cycling period) before turning on

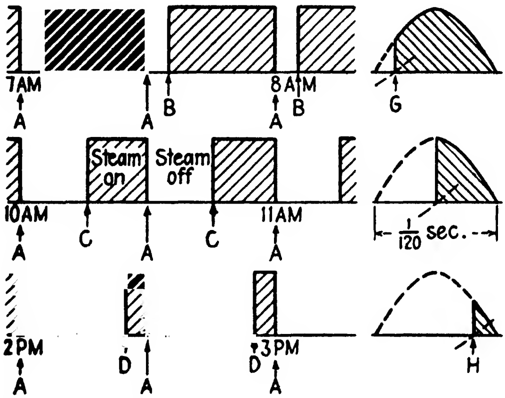


FIG. 13D. On-off steam valve acts like a phase-shifted thyratron.

the steam at C. Notice that the total or over-all amount of steam is less, as shown by the shaded blocks; yet the steam valve is either fully open or closed. If it is warmer yet by 2 P.M., the steam valve stays closed most of the time, but opens at D for a few minutes.

At the right in Fig. 13D, notice how each half cycle of a-c voltage (although lasting only $\frac{1}{120}$ sec) is like the 30-min period just described. At G, the thyratron (of Fig. 13F) is fired near the start of the half cycle; next it is shown firing near the middle, and at H it is firing near the end of the half cycle. In this way, a thyratron is made to control the *average* amount of voltage applied to its load, just as the on-off steam valve is made to control the average amount of heat.

13-5. Producing Voltages Out of Phase.—To fire a thyratron at a later point, the a-c curve of the grid voltage must be delayed

(see also Sec. 13-16); its phase must be shifted. Although the a-c grid voltage (in (*c*) of Fig. 13*A*) may be reversed or shifted 180 degrees out of phase merely by interchanging leads 1 and 2, this method cannot produce a gradual phase shift or give in-between amounts of shift. Instead, inside the phase-shifting rectangle (shown in (*d*) of Fig. 13*A*) a resistor is usually combined with a capacitor or an inductance, so as to produce a voltage out of phase with the input a-c voltage. Examples are shown in Fig. 13*E*.

In (*a*) of Fig. 13*E*, resistor 1*R* and capacitor 1*C* are connected in series across an a-c voltage that is in phase with the tube-1 anode voltage; one end of 1*R* is also connected to the tube-1 cathode, and the other end of 1*R* is connected to the grid.* The a-c voltage across resistor 1*R* is now the grid voltage of tube 1. What is the result?

In this circuit, where the same alternating current flows both in a resistor and in a capacitor, the current leads the voltage. This is shown in (*b*), where the current (*I*) wave rises above the zero line at *I*′, ahead (to the left) of the a-c supply voltage wave. We can show this in another way, by using a vector diagram† as in (*c*).

In (*c*) of Fig. 13*E*, the current *I* is shown to be 45 degrees ahead of the voltage. To see if this amount is correct, we must know the ohms of resistor 1*R*, and we must also calculate the ohms of capacitor 1*C*; (the capacitor ohms is the amount by

* Resistor *R* limits the amount of grid current when the grid potential becomes positive.

† A vector is a line drawn like an arrow. Several such lines may be drawn to form the triangles in Fig. 13*E*; here the *length* of each line shows an *amount* of voltage; the *direction* of the line and arrow shows whether that voltage is *ahead* of one of the other voltages. To explain this, suppose that the hour hand of a clock points at 3 o'clock. Two hours later, when the hand points at 5, the new direction of the hand shows a later time. In the same way, a vector arrow pointing in the direction of 5 o'clock lags, or is later than the 3 o'clock arrow; we say that the arrow pointing in the 5 direction lags 60 degrees behind the arrow pointing to 3. In our vector diagram of voltages, we use an arrow pointing in the 3 direction to represent the a-c supply voltage 1-2; this is the base line, or reference. Another arrow, pointing in the 5 direction, shows a voltage whose wave lags 60 degrees behind the a-c supply voltage. Similarly, a vector pointing at 12 o'clock is said to lead by 90 degrees, since such an arrow is 90 degrees ahead of the 3 o'clock arrow. A vector pointing at 7 o'clock lags 120 degrees.

which a capacitor resists the flow of alternating current).* In (*a*) of Fig. 13*E*, 1*R* is 25,000 ohms; the 0.1 mu f capacitor 1*C*

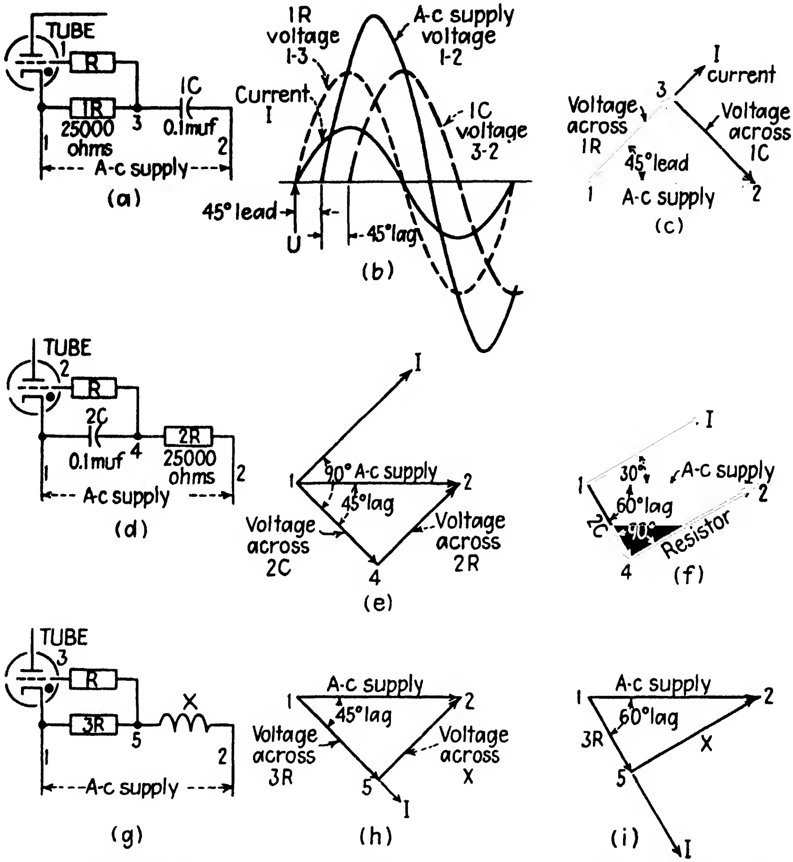


FIG. 13*E*.—Using resistors with capacitors or chokes for phase-shifting the grid voltage.

has 26,600 ohms (at 60 cycles, since 2660/0.1 mu f = 26,600). Notice that the 26,600 ohms of 1*C* and the 25,000 ohms of 1*R* are nearly equal; therefore the current *I* causes about the same

* The amount of ohms of a capacitor is quickly calculated when we know the size (microfarads or mu f) of the capacitor and the frequency of the a-c voltage applied to it. For any frequency *f*, the capacitor ohms = $1{,}000{,}000/2\pi f C$(mu f).

In a 60-cycle circuit, $2\pi f = 2 \times 3.1416 \times 60 = 377$;

so, at 60 cycles, capacitor ohms $= \dfrac{1{,}000{,}000}{377 \times \text{mu f}} = \dfrac{2660}{\text{mu f}}$.

amount of voltage drop across either $1R$ or $1C$. The vector triangle (c) shows the voltage 1-3 (across $1R$) by using a line about the same length as the voltage 3-2 (across $1C$); the voltage 1-3 across the resistor is in phase with current I (or points in the same direction as the I-current arrow). In this triangle, the current leads the supply voltage 1-2 by about 45 degrees.

Since the voltage 1-3 across $1R$ is also the grid voltage of tube 1 in (a) of Fig. 13E, this grid receives an a-c voltage wave similar to (c) of Fig. 13B; this grid voltage is not able to delay the firing of tube 1, so this circuit of (a) is not used for phase-shifting a thyratron; (it serves a special purpose in Fig. 11H). Instead, the circuit of (d) of Fig. 13E is used; here the current I leads the voltage 1-2 by 45 degrees, as before. The voltage across $2C$ is used as the tube-2 grid voltage; this capacitor voltage lags 90 degrees behind the current I (as shown in the vector diagram (e)), and lags about 45 degrees behind the supply voltage 1-2. This a-c grid voltage, therefore, delays the firing of tube 2, as shown in (a) of Fig. 13C. Since the vector 1-4 in (e) is about $\frac{7}{10}$ as long as the supply vector 1-2, we know that this grid voltage is about 0.7 of the a-c supply voltage 1-2.

If we use a 50,000-ohm resistor instead of $2R$ in (d) of Fig. 13E, the result is shown in (f)—more voltage across this resistor, less voltage across capacitor $2C$. The current I leads the voltage 1-2 by about 30 degrees, so the grid voltage 1-4 lags about 60 degrees. By increasing the resistance of $2R$ (or by using a larger capacitor for $2C$), the grid voltage lags farther behind the supply voltage, and fires tube 2 later, or farther behind its own anode-voltage wave.

13-6. Shifting a Voltage by Use of Inductance.—Like the resistor-capacitor circuits described above, an inductance (reactor or choke) may be used with a resistor, as shown in (g) of Fig. 13E; the voltage across resistor $3R$ is now the grid voltage of tube 3. In this circuit, where the same alternating current flows through a resistor and an inductance, the current I lags behind the voltage 1-2, as shown in the vector diagram (h). The voltage across resistor $3R$ (which voltage is in phase with current I) causes late firing of tube 3. If a smaller resistance (less ohms) is used as $3R$, the diagram (i) shows that the amount of current I increases; the grid voltage (across $3R$) becomes smaller and lags farther; tube 3 fires later.

The circuits of Fig. 13*E* will not phase-shift a thyratron more than 90 degrees or fire it later than the middle of the half cycle. To get a wider range of phase shift, the circuit of Fig. 13*F* uses two resistors 5*R* and 6*R* as a voltage divider; mid-point 7 is connected to the tube-4 cathode, while the grid is connected to 9, where *X* and 4*R* meet. The vector diagram is like (*i*) in Fig. 13*E*, but Fig. 13*F* adds the vector 7-9, which shows the direc-

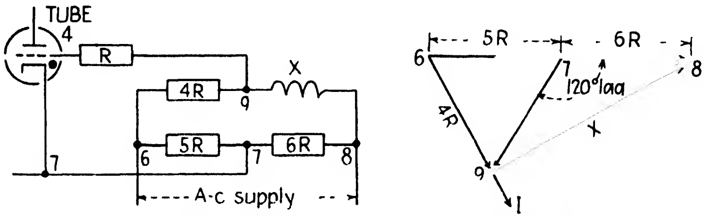


FIG. 13*F*. Phase-shifting more than 90 deg.

tion of the tube-4 grid voltage. Notice how this grid voltage lags about 120 degrees behind the a-c supply voltage 6-8; it fires tube 4 very late in the half cycle, as shown at *H* in (*b*) of Fig. 13*C*.

In place of the voltage divider 5*R* and 6*R* in Fig. 13*F*, industrial circuits often use a transformer winding with a center-tap, as shown in Fig. 13*O*.

We need not connect the tube-4 grid or cathode directly to the phase-shifting circuit, as is done in Fig. 13*F*; we may use a

FIG. 13*G*.—Transformer 3*T* separates tube 4 from the phase-shifting bridge.

grid transformer, as shown at 3*T* in Fig. 13*G*. Resistors 4*R*, 5*R* and 6*R* now combine with *X* to shift the phase of the a-c voltage supplied to the primary of 3*T*; Fig. 13*G* shows this primary-voltage vector as before, 7-to-9. Using 3*T* in this way, its secondary voltage (which is also the grid voltage of tube 4) may be any size; at *BA* its vector is shown smaller than 7-9. The vector arrow *BA* is shown pointing in the same direction

as 7-9. If we interchange the two terminals (connecting A instead to the cathode, B to the grid), the vector of grid voltage is also reversed; the dashed line AB points upward so as to lead the a-c supply voltage 6-8.

13-7. Variable Inductance in a Phase-shifting Bridge.—Figure 13H shows a circuit often used for adjusting the grid phase of thyratrons. (See also Sec. 16-4, where a saturable

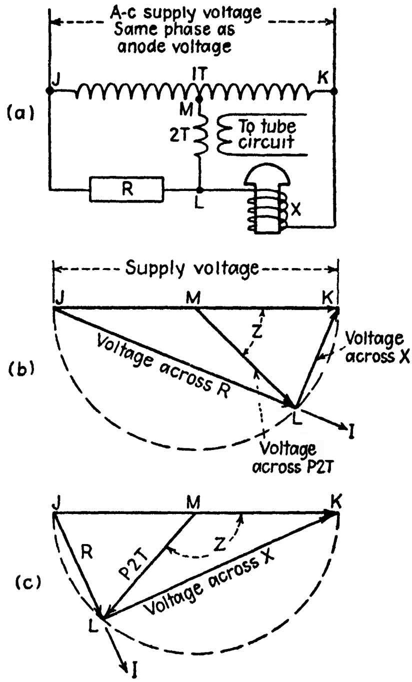


FIG. 13H.—Phase-shifting by using variable inductance.

reactor acts like the variable inductance X of Fig. 13H.) Here we have a transformer $1T$ across an a-c supply JK, of the same phase as the tube anode voltage. This transformer has a convenient mid-tap connection at M for one primary lead of transformer $2T$. Also across the alternating current supply is a reactor X and a resistor R in series with it. Their common point L is connected to the remaining primary lead of $2T$. The voltage of a secondary winding of $2T$ is applied between the grid and the cathode of the tube whose current we wish to control.

A reactor (such as X) usually is made of a large number of

turns of wire wound around an iron core. Figure 13*H* shows a reactor with a movable iron core (like a solenoid). Withdrawing the core decreases the amount of effective iron. With less iron, the reactor has less inductance; that is, it is less able to prevent the flow of alternating current through its windings. If the core of the reactor X (in the circuit shown in Fig. 13*H*) is removed, the small inductance of X produces the short voltage arrow, "voltage across X," in the vector diagram in (*b*) of Fig. 13*H*.*

If the iron core is now put back into reactor X, its inductance increases, causing a decrease of current I flowing through X and R. Since inductance X has increased while R remains unchanged, the vector voltage across X has increased, as is shown by the vector LK in (*c*) of Fig. 13*H*. Again at a right angle to LK, we show JL, the voltage drop across resistor R. This voltage across R has decreased. As a result of these changes, vector ML (voltage across 2*T* primary) has swung clockwise, so that the tube grid voltage now lags by a much greater angle Z. The resulting relationship between the tube anode voltage and tube grid voltage is shown in (*b*) of Fig. 13*C*. Since the tube is kept from firing until point H, and passes current for only a small portion of each half cycle, the average current is much less than before. We see that by increasing the inductance of X we have caused a corresponding decrease in tube anode current.

* When a reactor is connected alone across an a-c voltage, the current in that reactor lags the applied voltage. In contrast, a resistor passes current that is in phase with the applied voltage. When reactor X and resistor R are connected in series as in Fig. 13*H*, and are connected across an a-c supply, the same current flows through both R and X, so the voltage across R always lags 90 degrees behind the voltage across X. In (*b*) of Fig. 13*H* we see that the voltage across R (represented by vector JL) and the voltage across X (represented by vector LK) are at right angles to each other; vectorially added together, they equal vector JK (which is the supply voltage). Between the mid-point M and the 90-degree-angle junction L is a voltage (ML) that lags at some angle Z behind the supply voltage JK. This voltage ML is applied to the primary of transformer 2*T*; the secondary winding of 2*T* furnishes voltage at this angle Z, to the grid of the tube to be controlled. For the conditions shown in (*b*) of Fig. 13*H*, where the voltage across X is smaller than the voltage across R, the tube grid voltage (supplied by 2*T*) lags by only the small angle Z behind the supply or tube anode voltage; the result appears in (*a*) of Fig. 13*C*

13-8. Phase-shift Control of Alternating Current.—So far we have studied a single thyratron tube and the phase-shift control of its grid circuit. Let us now connect two tubes back to back,[9-5] to act as an alternating-current switch, and watch them as they supply current to an inductive load. (Later we can extend this circuit to handle a large welding-transformer load, merely by letting each thyratron fire an ignitron somewhat as in (*b*) of Fig. 13*A*.) In (*a*) of Fig. 13*I* each of these tubes is controlled by its own separate grid circuit—*S2T*-1 supplies the a-c grid voltage to tube 1. However, since the current flowing through the transformer load is alternating current, we show the voltage and current wave as in (*b*) of Fig. 13*I*. Here we see that the grid voltage (*S2T*-1) lags the anode voltage so that tube 1 starts to pass current at point *G*, yet the resulting current wave of (*b*) appears to be a continuous sine wave. When tube 1 is fired at point *G*, the current through the inductive load cannot increase abruptly, but increases gradually to its maximum at *H*, and continues to flow until *I*. However, *I* is the same as point *R*, where tube 2 is fired by its own grid voltage from *S2T*-2, so the current now starts to flow through tube 2. This is merely a detailed way of saying that this inductive load draws current at a lagging power factor—the current wave lags about 45 degrees behind the supply-voltage wave. Since we fire tubes 1 and 2 at this same 45-degree angle (the normal power-factor angle of this load), a complete sine wave of current flows through the transformer load.

If we now retard or phase-shift the a-c curves of grid voltage so as to delay the firing of thyratron tubes 1 and 2, until a point is reached about 90 degrees behind the supply-voltage curve, (*c*) of Fig. 13*I* shows that the current starts to flow through tube 1 at point *J*. The inductance of the load permits the current to increase at the same rate (as before in (*b*)), but the current has risen only as high as *K* before the a-c voltage decreases at the end of the half cycle, letting the current die out at *L*. There is no further current flow until tube 2 is fired by *S2T*-2 at point *M*.

We notice that the height of the curve at *K* is lower than at *H*; however, we now realize that this decreased current is not due to any grid control of the instantaneous current flow, but that it is due to the combined effect of the inductive type of

load and the delayed firing of tube 1. If the firing of the thyratrons is further delayed until a point about 135 degrees behind the supply voltage is reached, current then flows as shown by

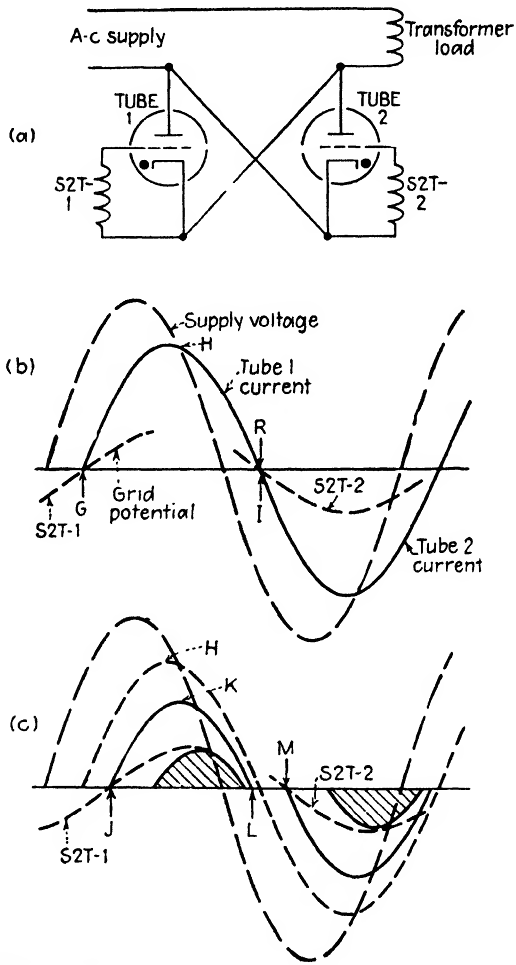


FIG. 13*I*.—Decreasing the amount of alternating current by phase-shift control.

the shaded portions in (*c*) of Fig. 13*I*. This method of decreasing the amount of current flow is just as effective as though the current were reduced by an autotransformer or a series resistor. When used to control the current flow through tubes to a welding transformer, this method is called phase-shift heat control.

13-9. Welder Heat Control (CR7503-D137).—This panel may be added to a standard ignitron contactor so as to phase-shift the ignitron tubes and provide variation of the welding current or "heat." Figure 13*J* shows the basic circuit of this heat control. Notice that the thyratron tubes 5 and 6 are con-

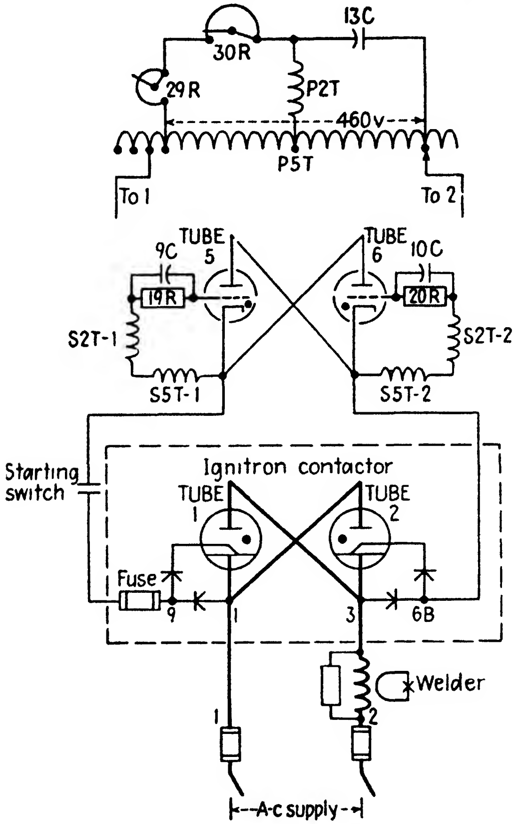


FIG. 13*J*.- Welder heat control added to an ignitron contactor.

nected as an a-c switch in series with the starting switch of the ignitron contactor. With the starting switch closed, ignitron tube 1 can pass current to energize the welding transformer, only when thyratron 5 fires; tube 6 similarly controls ignitron 2.

In Fig. 13*J* the grid circuit of thyratron 5 includes two transformers* instead of the single one previously described. The

* Figure 12*H* shows two transformers used in this way, in the grid circuit of tube 6.

combined waveshape of these transformers is shown in Fig 13*K*. Notice that the voltage of *S5T*-1 is an ordinary sine wave, but *S2T*-1 furnishes a narrow voltage peak that is high enough to force the tube grid positive for just a small part of the half cycle; this brief voltage peak* fires tube 5 at *A* and *B*. If we can change the position of this peak, we also change the point in the half cycle where tube 5 fires. If the voltage applied to the primary of 2*T* is in phase with the a-c supply, the voltage peak of *S2T*-1 appears very near the beginning of the half

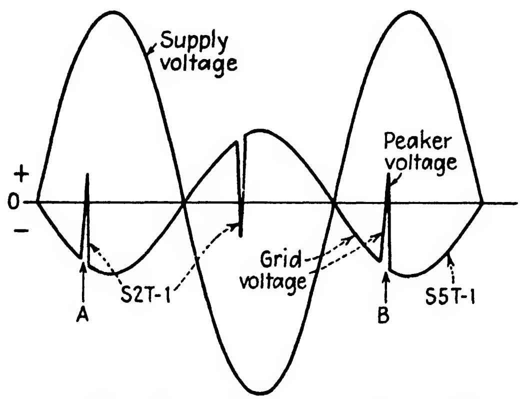


FIG. 13*K*. Voltage peak used for delayed firing.

cycle. However, if we phase-shift 2*T* (by applying to its primary a voltage that lags the a-c supply voltage), the peak of *S2T*-1 occurs later in the half cycle of supply voltage, as is shown in Fig. 13*K*.

13-10. Variable-resistor-capacitor Bridge.—In Fig. 13*J*, tube 5 is fired by the voltage peak of *S2T*-1 in its grid circuit. Notice the primary *P2T* of this peaking transformer connected in the upper part of Fig. 13*J*, which is a phase-shifting circuit somewhat like that of Fig. 13*H*. Figure 13*J* uses a variable resistor† 30*R* for adjusting the phase angle of the voltage applied to *P2T*; meanwhile, capacitor 13*C* remains constant. If 30*R* is turned

* Transformer 2*T* is a peaking transformer, described in Sec. 28-5 and used before in Sec. 12-15.

† Assume here that 29*R* is shorted. In service, part of 29*R* is left in circuit so that the *S2T* voltage peak cannot occur earlier than the point that gives the full "heat" at the welder, even though 30*R* is turned until its resistance is all shorted.

until all its resistance is shorted, then *P2T* is connected directly across part of *P5T* (connected to the a-c supply); the voltage peak of *S2T*-1 then occurs near the beginning of the half cycle.

If 30*R* is now turned so as to insert some resistance, the corresponding vector diagram* ((*a*) of Fig. 13*L*) shows that the voltage applied to *P2T* here leads the supply voltage by perhaps 135 degrees. However, by properly connecting the secondary leads of *S2T*-1, we obtain the voltage peak *S2T* at a position about 45 degrees behind the supply voltage. As was previously shown in (*b*) of Fig. 13*I*, firing at this 45-degree angle may provide approximately a complete sine wave of current flow through the tubes, or full "heat" at the welder.

When we further increase the resistance in 30*R*, the vector diagram becomes like (*b*) in Fig. 13*L*. The amount of current *I* is less, the voltage decreases across 13*C*, increases across 30*R*; notice that the size of the vector *P2T* is not changed, so the amount of *S2T* (height of voltage peak) is not changed. The peak of *S2T* moves to the right, or occurs later in the half cycle; tube 5 fires later, passes less average current and causes less "heat" at the welder. This condition is shown in Fig. 13*M*.† When tube 5 fires, because of the *S2T*-1 voltage peak at *C*, current flows through tube 5 and the ignitor of ignitron 1, but flows only long enough to fire the ignitron. The shaded area

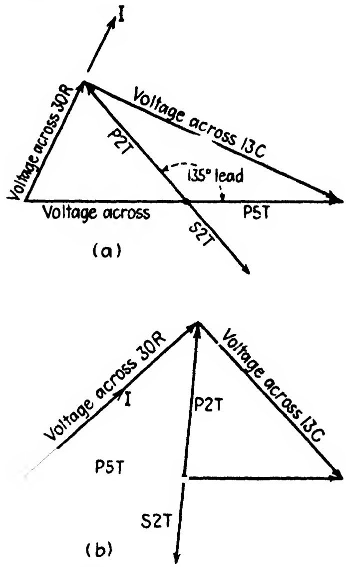


FIG. 13*L*.- Vector diagrams at several settings of 30*R* in Fig. 13*J*.

* Similar to (*a*) and (*c*) of Fig. 13*E*, except that transformers 2*T* and 5*T* are added.

† In Fig. 13*M*, notice that the voltage of *S5T*-1 is 180 degrees out of phase with the anode voltage of tube 5. As a further precaution to prevent tube 5 from firing at point *A*, we insert 19*R* and 9*C* in the grid circuit, as shown in Fig. 13*J*. By grid rectification,[5-4] *S5T*-1 forces current through 19*R*, charging 9*C* so that it is more negative at the grid connection. The result is shown at *B* (in Fig. 13*M*) where the grid potential has been made so negative that tube 5 cannot fire accidentally.

of Fig. 13*M* represents the combined current flow, first in tube 5, immediately followed by ignitron 1.

If we now turn 30*R* to insert all its resistance, the peak of *S2T* occurs very late in each half cycle, as is shown in Fig. 13*N*; the shaded area shows the decreased current flow that results

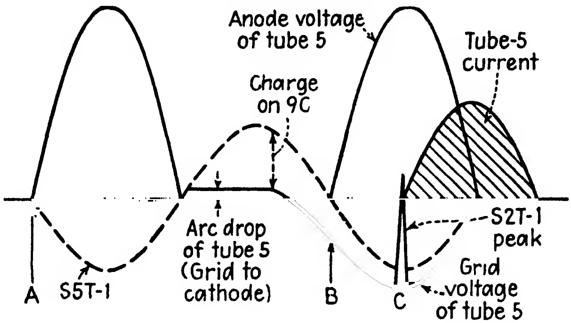


FIG. 13*M*.—Voltages in thyratron grid circuit at medium weld heat.

in very low heat at the welder. We see that by turning resistor 30*R* we can gradually control the amount of tube current and the welder "heat."

The heat control described provides not only an accurate stepless means of varying the welder "heat," but gives more

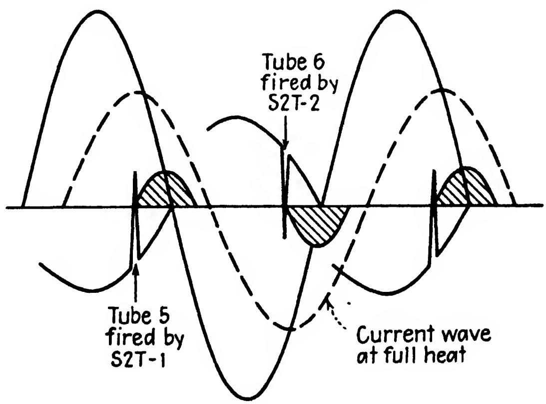


FIG. 13*N*.—Voltage waveshapes of thyratrons (Fig. 13*J*) at low heat.

consistent welding results by starting successive welds at exactly the same point on the voltage wave.

13-11. Welder Heat Control (Westinghouse Type).—This phase-shifting circuit, shown in Fig. 13*O*, uses a center-tapped

a-c input transformer A-B, a reactor X and resistor $1R$.* (This inductance-resistance bridge circuit is like Fig. 13G, described in Sec. 13-6, except that the positions of X and IR are interchanged; the vector triangle appears above the horizontal line instead of below it.) Although this complete circuit may adjust or phase-shift the tube-5 grid voltage, as explained below, no change is made in the amount of inductance X or resistance IR in the circuit; the vector triangle ABD (shown at (a) in Fig. 13P) always has the same shape. The voltage CD cannot be changed and is not used.

To get a variable voltage for the tube-5 grid transformer $4T$, resistor $2R$ is added; taps are provided on X, and sliding con-

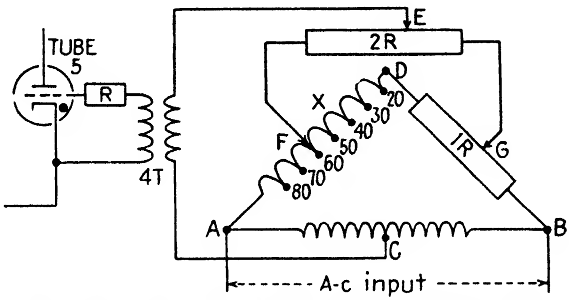


FIG. 13O.—Phase-shifting circuit (Westinghouse type).

tacts on $1R$ and $2R$. On X, contact F is connected to the tap having a number close to the power factor of the welder, to prevent tube 5 from firing ahead of the full "heat" point.† On $1R$, contact G is adjusted to prevent tube 5 from firing too late in the half cycle. After being adjusted for use with a certain welder, F and G remain fixed, and contact E is then moved to shift the tube-5 grid voltage and change the welder heat.

Suppose that F is connected to tap 80 on X, while slider G is moved near to the D end of $1R$. The vector result appears in (b) of Fig. 13P. The broken line from F to G is also the voltage across resistor $2R$; if slider E is near the middle of $2R$, it is at that potential near the middle of line FG. The vector CT

* LAWSON, T. R., Resistance Welds With Electronic Control, *Westinghouse Engineer*, November, 1942.

† A similar adjustment is made with $29R$ in Fig. 13J. See Sec. 13-10, footnote.

shows the voltage now applied to the primary of grid transformer $4T$; the secondary voltage of $4T$ lags by the angle W and fires tube 5 nearly 90 degrees late. Slider E may be moved from one end (at potential F) to the other extreme at G; at the F end, vector CR is the voltage applied to grid transformer $4T$, so tube 5 fires quite early in the half cycle (but never ahead of the 80 per cent power-factor point). When slider E is at the

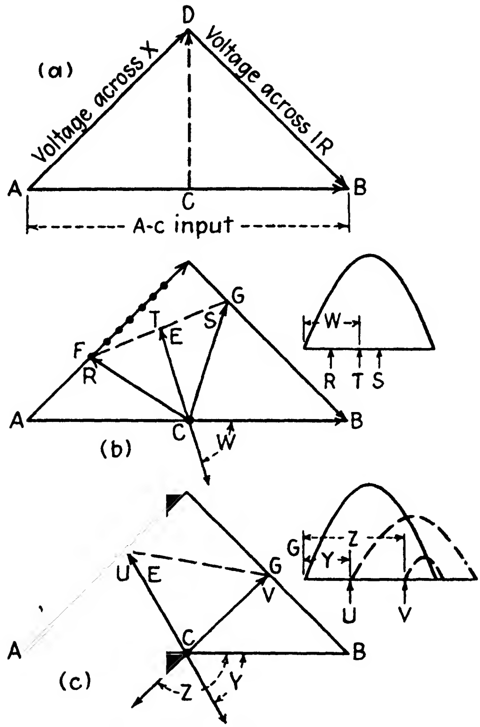


FIG. 13P.—Vector diagrams for Fig 13O.

G end, vector CS shows the voltage which (through $4T$) fires tube 5 at S. (Notice that no position of slider E will fire tube 5 earlier than R or later than S.)

A more usual adjustment is shown in (c) of Fig. 13P; here F is connected to the 50 tap of X, while G is set to give a firing point not later than 135 degrees. Now, when slider E is moved to the "full-heat" position, vector CU lets tube 5 fire at point U (which is the right place to close the circuit to obtain a full sine wave of current flowing in a 50 per cent power-factor welder).

The minimum heat, when slider E is moved to the G end, is given by vector CV; tube 5 fires at point V, and welding current flows for only a small part of the half cycle.

13-12. A Half-cycle Magnetizer (CR7509-D110).—In magnetizing a piece of metal by electricity, a large direct current must flow near or through the metal piece to produce a strong magnetic field. This large current must flow in one direction only, and may flow for a very short time. A half cycle of a-c power may be used, if it is properly controlled. Instead of taking the large current directly at the a-c supply voltage, a transformer is used. Here, as in any transformer, the large secondary output current (perhaps 40,000 amperes is needed for magnetizing) results when the transformer flux changes. Therefore, a magnetizing equipment aims to produce a large change of flux in the transformer, once for each piece to be magnetized.

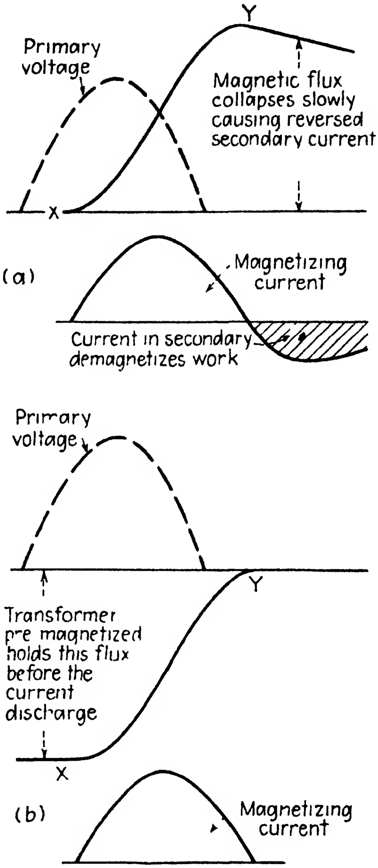


FIG. 13Q Two ways of producing current for magnetizing a steel part

Figure 13Q shows two ways in which this change in flux (from X to Y) may be applied; the first is not so good as the second. In (a), after the metal piece is clamped into the secondary circuit of the magnetizing transformer, primary current flows for about a half cycle, so as to increase the transformer flux from X to Y; this magnetizes the metal piece. However, this large magnetic flux must then drain out of the transformer; as the flux decreases, a current flows in the transformer secondary, smaller than before but in the opposite direction; this current

partly demagnetizes the metal piece, so that some pieces remain magnetized more strongly than others. To avoid this action, (b) shows the use of a transformer that is pre-magnetized, because a small current already has been flowing through its primary winding in the reverse direction; this premagnetizing current produces the large transformer flux, before magnetizing the metal piece. Then, when a half cycle of current flows in the primary winding, in the forward direction, the transformer flux changes from X to Y. Notice that this flux changes in the same direction in both (a) and (b), and produces the same magnetizing current. However, in (b) the flux is decreasing; any remaining flux continues to decrease in the same direction, so the secondary current does not reverse; the metal piece is not partly demagnetized.

The magnetizing action shown in (b) is given by the circuit of Fig. 13R; here the main current flows for a half cycle, and these electrons flow from line 1 through the ignitron tube 3 to point 3, and through the primary of the magnetizing transformer to line 2. (Resistor 14R adds enough "dummy" load to make sure that the total current is large enough[9-6] for the best operation of ignitron 3.) Ignitron 3 is fired by thyratron tube 2, but not until after the transformer has been premagnetized by current flowing through thyratron tube 4.

13-13. Magnetizer Circuit Action.—In Fig. 13R, tubes 1 and 5 rectify the a-c supply to produce about 500 volts d.c. between points 4 and 5, and also between 5 and 6. (While tube 1 rectifies full wave, tube 5 is connected as a half-wave rectifier, which uses the left half of transformer S2T during the same half cycle when the right-hand anode of tube 1 is using the right half of S2T.)

Before the starting switch is closed, the n-c contacts of relays 2CR and 3CR are closed, so capacitors 3C and 4C are both charged. The voltage across 4C holds point 7 more negative than point 5 (cathode of tube 2) by 500 volts, so the voltage peaks of peaking transformer S1T are not high enough to fire tube 2. Neither does tube 4 pass current, for the 3CR contact is open beneath tube 4.

After the metal piece or load is clamped to the magnetizing-transformer secondary, the starting switch is closed to pick up 2CR and 3CR. Tube 4 immediately passes electrons, which

flow from line 2 through the magnetizing-transformer primary to 3, through 3*CR* contact, tube 4 and 13*R* to line 1. (At this time the control grid of tube 4 is kept positive by the small voltages of *S*2T and *S*3*T*.) As is shown at *A* in Fig. 13*S*, these pulses of current through tube 4 gradually increase the magnetic flux* of the transformer; this premagnetizing current flows for about 1 second before the next action starts. To control the length of the premagnetizing time, the charge on capacitor 4*C* in the grid

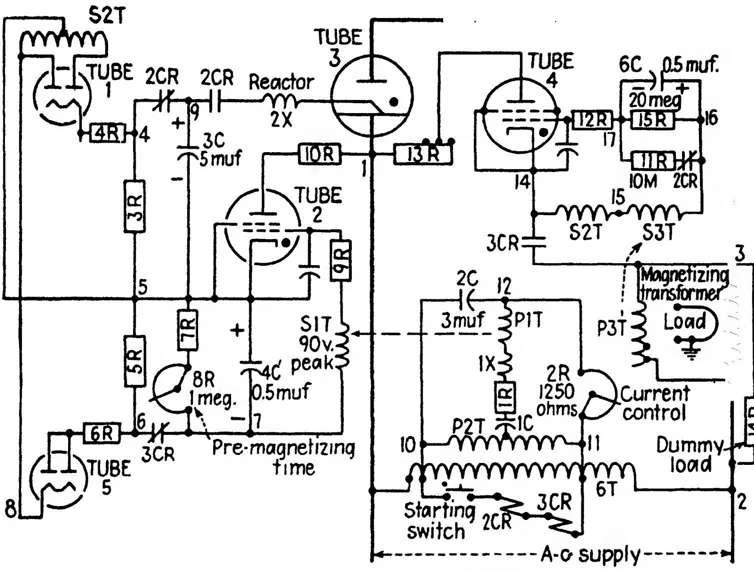


FIG. 13*R*.- Circuit of a half-cycle magnetizer (CR7509-D110).

circuit of tube 2 keeps tube 2 from firing until 4*C* has discharged through 7*R* and 8*R*; 8*R* is adjusted to give 1 to 2 seconds' time delay before a voltage peak of *S*1*T* can fire tube 2, at *B* in Fig. 13*S*. When tube 2 fires, the energy stored in capacitor 3*C* forces electrons to flow from point 5 through tube 2, 10*R*, pool to ignitor of tube 3, through 2*X*† and the 2*CR* contact to point 9. This fires ignitron tube 3, which passes about a half cycle of current to cause the magnetizing action. (Although the tube-2

* The flux remains nearly constant between current pulses, since the transformer secondary is short-circuited by the metal piece.

† Reactor 2*X* limits the rise of discharge current from 3*C*, to give longer ignitor life.

grid is made positive by later $S1T$ peaks, there is no anode voltage until capacitor $3C$ recharges; this happens only when the starting switch is released.) The exact amount and length of flow of magnetizing current depends on the phase-shifting circuit of the peaker voltage $S1T$, as described below.

After ignitron 3 fires, tube 4 must be kept from firing or its current may partly demagnetize the metal piece. So, when the

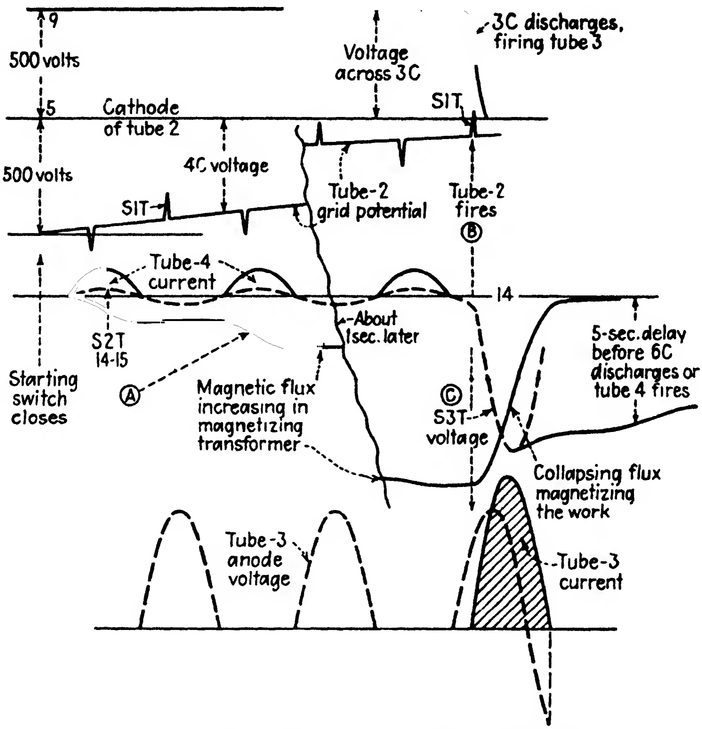


FIG. 13S.– Waveshapes in the action of Fig. 13R.

magnetizing transformer receives its voltage through ignitron 3, this voltage also energizes $P3T$, whose secondary $S3T$ is in the grid circuit of tube 4. As shown at C in Fig. 13S, the voltage of $S3T$ charges capacitor $6C$, by electrons flowing from terminal 15 through $S2T$, cathode to control grid of tube 4, through $12R$ and $15R$ to 16. The time constant[4-5] of $15R$ and $6C$ is long, so that tube 4 cannot fire for about 5 seconds; the operator has time to remove the magnetized metal piece. The starting switch is then

released; a n-c contact of 2*CR* shorts 15*R* through a lower resistance 11*R*. The equipment is ready for the next operation.

13-14. Control of Amount of Magnetizing Current.—Greater magnetizing current is obtained by firing tubes 2 and 3 earlier in the half cycle of a-c voltage; to do this, the *S*1*T* voltage peak is advanced by the phase-shifting circuit in Fig. 13*R*, shown above the starting switch. This circuit combines capacitor 2*C* with variable resistance 2*R* so as to shift the phase of the voltage applied to the primary winding *P*1*T* as already described.[13-10]

In series with *P*1*T* are reactor 1*X*, capacitor 1*C* and resistor 1*R*. These add nothing to the normal operation of *P*1*T*, and so are not shown in the phase-shifting bridges of Figs. 12*J* or 13*J*; such parts are included also in those equipments. 1*X* and 1*C* combined act as a filter, resonant* at 60 cycles; the 60-cycle power passes easily through this combination, but impulses or voltage surges at other frequencies are prevented from reaching *P*1*T*. Owing to its special design, this peaking transformer will give false operation if the voltage across *P*1*T* changes or dips at any time other than when the 60-cycle voltage crosses the zero line.

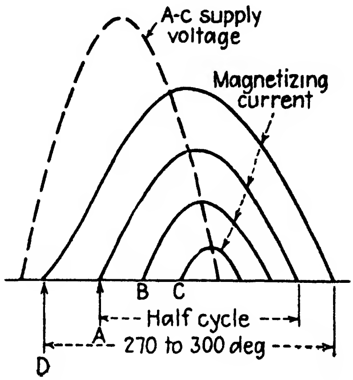


FIG. 13*T*.—Firing point controls the amount of magnetizing current

The magnetizing transformer of Fig. 13*R* has a value of power factor, like any welding transformer. If 2*R* is set so that the voltage peak of *S*1*T* fires tubes 2 and 3 exactly at this power-factor angle, as shown at *A* in Fig. 13*T*, then the magnetizing current flows for 180 degrees, or exactly a half cycle of time. If more of the 2*R* resistance is inserted, the current starts to flow later (as at *B* or *C*) and ends sooner than before; as a result, the current wave is not so high, the magnetizing-transformer flux changes more slowly and the metal piece is not so strongly magnetized.

* To be resonant at 60 cycles, the size of capacitor (in mu f) and the size of reactor (in henrys) are chosen so that, when frequency $f = 60$, then $2\pi fL(\text{henrys}) = 1{,}000{,}000/2\pi fC(\text{mu f})$.

If all the $2R$ resistance is shorted, the current starts to flow at D, or just as soon as there is enough anode voltage to let ignitron 3 fire. Since this current starts ahead of the power-factor angle, the current rises higher; this current is the first positive portion of the transient wave in Fig. 12F, starting at W.

13-15. Phase-shifting Methods.—There are several types of grid-circuit arrangement that can gradually change the firing point of a thyratron.

1. In those phase-shifting circuits now described, the thyratron firing point is shifted by moving the whole a-c curve of grid voltage to the left or to the right; to do this requires a combination of resistance and capacity or inductance, one of which must be variable.

2. In another method (described in Sec. 15-5), the thyratron grid circuit includes a constant a-c voltage wave, whose phase position remains fixed, so that it lags perhaps 90 degrees behind the thyratron anode voltage at all times. Gradually this entire a-c voltage wave is then raised or lowered, because of a variable d-c voltage in the grid circuit; in some circuits this d-c voltage is increased or decreased by the action of a high-vacuum tube. In this kind of circuit, when the current in a high-vacuum-tube anode gradually changes by less than a millampere, the thyratron current may also change gradually, through a range of several amperes.

3. A third method uses no sine wave of a-c voltage in the grid circuit; instead, the thyratron grid responds to a different waveshape, such as the sloping voltage curve produced by a slowly discharging capacitor. Figure 11G shows such voltage waves; similar discharge waves are used in Sec. 25-7 and in the thyratron grid circuits in the next chapter.

Questions

True or false? Explain why.

1. The glow seen in a vapor-filled tube is brighter when the tube is fired earlier in its half cycle.

2. Phanotrons may be phase-shifted.

3. Voltages from many separate transformers may be used in a single grid circuit.

4. An a-c voltmeter, connected anode to cathode across thyratrons in a 440-volt a-c circuit, will read only 440 volts or 15 volts.

5. A d-c voltage may be phase-shifted.

6. In many circuits 25 to 150 volts a.c. is applied directly to the grid of a thyratron.

7. Any voltage that becomes more positive while the tube anode is positive (on a-c supply) may be used to phase-shift this tube.

8. The size (height to the crest of the wave) of a voltage always changes when it is phase-shifted.

9. In a 60-cycle circuit using 10,000 ohms and 0.5 mu f for phase shifting, the results are the same if 50,000 ohms and 0.1 mu f are used, instead.

10. If the amount of anode current (of a thyratron) could be controlled each instant by the grid potential, there would be no need for phase shifting.

11. A thyratron may be phase-shifted by a-c grid voltages that lag the anode voltage, but not by a voltage wave that leads the anode voltage.

12. A voltmeter, connected across a load supplied through phase-shifted thyratrons, must read more than 15 volts or the tubes fail to fire.

13. To phase-shift equally two tubes connected back to back, the a-c grid voltage of one tube must be in phase with the a-c grid voltage of the other tube.

14. Which of these pairs produce a 60-cycle voltage (between the *R*-and-*C* joint and the mid-tap of the a-c supply) which is about 90 deg out of phase with the supply?

(*a*)	C = 1 mu f,	R = 1 megohm
(*b*)	0.1 mu f,	1000 ohms
(*c*)	0.0025 mu f,	1 megohm
(*d*)	0.001 mu f,	0.2 megohm
(*e*)	C = 1 mu f,	R = 2500 ohms
(*f*)	0.2 mu f,	13,000 ohms
(*g*)	0.03 mu f,	20M
(*h*)	0.05 mu f,	50M

15. Which of the above pairs produce a voltage across the resistor that is about 90 deg out of phase with the a-c supply?

CHAPTER 14

HEATING AND LIGHT-DIMMING CONTROLS

In the preceding chapters large alternating currents pass directly through vapor-filled tubes; control of these tubes permits the control of large a-c loads, off and on, many times each second. Other large a-c loads may be turned on or off more slowly, such as the electric heaters in industrial furnaces, or large groups of lamps used for the lighting of theaters or displays. To hold accurately the desired temperature or amount of light, and gradually to change these amounts when desired, tubes need not directly carry or conduct the load current; smaller tubes may be used, together with a saturable reactor.[28-6] The following circuits show how, using such a reactor, a large a-c load (of up to hundreds of amperes and kilowatts) may be controlled by a small direct current (part of an ampere). In this way, small electron tubes may control much larger a-c circuits; the saturable reactor is the connecting link, and acts like a large power amplifier.

14-1. Control of A.C. by Rheostat or Reactor.—The amount of alternating current passing through a load may be changed or controlled by using a rheostat, or variable resistor, such as R in Fig. 14A. This rheostat must carry the load current through its own resistance and its sliding contact. While well suited to small currents, such a rheostat is used less often to handle large currents, for it has large heat losses; too much force is needed to move the sliding contact, which must be carefully maintained.

Instead of a variable resistor, a variable reactor or inductance may be used in the a-c circuit, as shown at SX in Fig. 14A; SX is called a saturable reactor, and is explained in Sec. 28-6 The alternating current passes through the high-current winding of SX to reach the load; the amount of this alternating current depends on how much direct current flows in the small d-c winding connected to the battery. If there is no d.c., SX has large inductance or greatest action as a choke to prevent the flow of a.c. In Fig. 14A, part (C) shows that most of the a-c supply

voltage is now across SX and very little voltage is across the load; SX acts like R with all its resistance in circuit, or nearly like an open switch.

When the small dial resistor P is turned clockwise, the battery forces a small direct current through the d-c winding of SX (which is not connected to the a-c winding of SX). This d.c. partly saturates the iron core of SX, decreasing its choke effect so that a larger alternating current may flow through SX and the load; (*d*) shows that perhaps half of the a-c supply voltage is now across the load. If P is entirely shorted, the current in the d-c

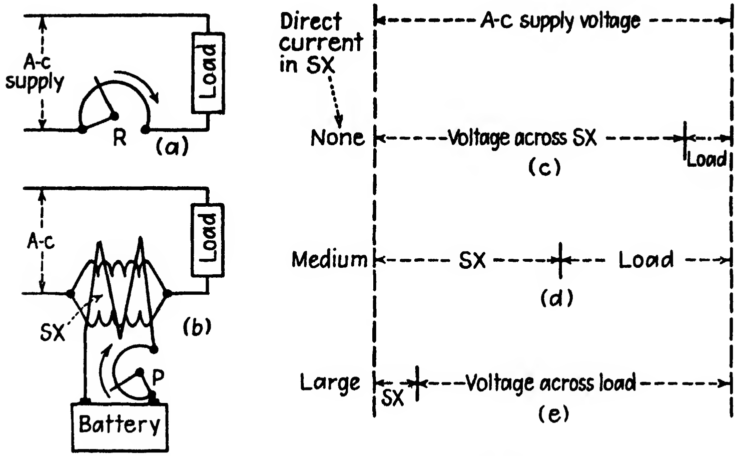


FIG. 14*A*.- Saturable reactor gradually may change the a-c load voltage.

winding of SX may yet be much less than an ampere; however, SX has lost most of its choke effect so that the a-c load current is nearly as great as when SX is entirely short-circuited. Nearly the whole a-c supply voltage is across the load, at (*e*).

There is no electronic equipment in Fig. 14*A*. Notice that the dial resistor P may be several inches across, yet turning it controls an a-c load of hundreds of amperes. The reactor SX may be large and heavy, but it may be in another part of the building, far from the small dial P.

14-2. A Battery-charging Regulator.—A saturable reactor is used again in Fig. 14*B* to control the amount of a-c voltage applied to the primary of transformer T. The secondary voltage of T is rectified by two phanotrons; the resulting voltage, A-to-B, is used

to charge a 144-volt storage battery.* As long as the contact of relay *CR* is held closed (by the spring shown above it), electrons flow from *B* to *D*, through the d-c winding of *SX* to *A*; this current saturates *SX*, so that most of the a-c supply voltage is

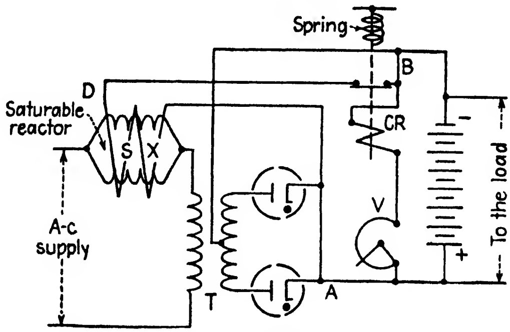


FIG. 14B.—Battery-charging regulator using a saturable reactor.

applied to *T*. The *T* secondary voltage is so large (at *J* in Fig. 14*C*) that it causes pulses of current *K* to pass through the tubes and charge the battery.† This current flows only during the

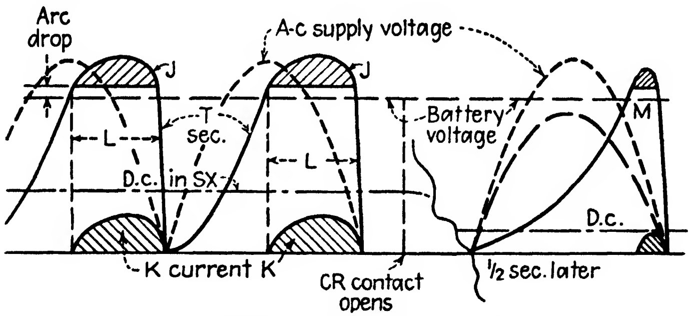


FIG. 14C.—Waveshapes in the circuit of Fig. 14B.

latter part (*L*) of the cycle, when the *T* secondary voltage is at least 15 volts (tube arc drop) higher than the battery voltage.

Rheostat *V* in Fig. 14*B* is set for the desired battery voltage. When charging current raises the battery voltage as high as

* An all-tube battery charger is described later.[25-9] A similar combination of variable inductance, anode transformer and phanotrons is used in a d-c motor controller.[15-8]

† The odd waveshape of *T*-secondary voltage results from the action of the saturable reactor, which has much less inductance near the end of each half cycle, as explained in Sec. 28-7.

desired, this high voltage forces enough current through the *CR* coil so that the coil pulls open the *CR* contact; this stops the flow of current through the d-c winding of *SX*. The voltage across transformer *T* decreases, so its secondary voltage (shown at *M* in Fig. 14*C*) is too small to force much current through the battery. (Reverse current cannot flow or discharge the battery, because of the rectifier action of the phanotron tubes.) However, as load current slowly lowers the battery voltage, soon the *CR* coil can no longer hold the *CR* contacts open; direct current flows again in *SX*, the *T*-secondary voltage returns to height *J*, again charging the battery.

14-3. Theater Light-dimming Control (CR7502).*—To dim the lights to any desired level, the voltage across each group of lights may be reduced by a "dimmer plate" (like rheostat *R* in Fig. 14*A*). Large modern theaters have hundreds of light groups, each needing separate control; this number of hand-operated dimmers takes too much space and causes too much heat. Instead, the current for each group of lights is adjusted by a saturable reactor;[28-6] Fig. 14*D* shows the circuit used for a single group of lights. With such a system, the reactors and tube controls may be placed far away; only the light-adjusting lever *B* needs to be at the control desk near the orchestra pit. Such levers, for hundreds of lighting circuits, are mounted close together; by the joining of their circuits through small switches, dozens of light groups are controlled by moving one lever.† Just a single reactor and tube circuit is described below.

At the left side of Fig. 14*D*, the a-c supply voltage is increased about 10 per cent by booster transformer *T*; this boost about equals the voltage drop across the saturable reactor *SX* when it is fully saturated, and the lights are turned full on; in this way, lamps of usual line-voltage rating may be used, although they are in series with the reactor.

To furnish direct current for the saturating winding of *SX*, a thyratron *T* and phanotron *P* are used. When we increase the anode current of *T* (by control of its grid), the inductance or choke effect of *SX* decreases and makes the lights brighter.

* The description of this circuit applies also to the furnace-heat control of Sec. 14-8.

† SCHNEIDER, E. D., Thyratron Reactor Lighting Control, *Electrical Engineering*, June, 1938.

Later we will see how tube A and capacitors $1C$ and $2C$ control the grid of T.

Since tubes T and P are connected in a manner not yet described, let us first study this action of tubes in an inductive circuit. (The d-c circuit of reactor SX is highly inductive, so that nearly a second is needed before the direct current reaches its full amount.) Figures 14E, 14F and 14G are basic steps by

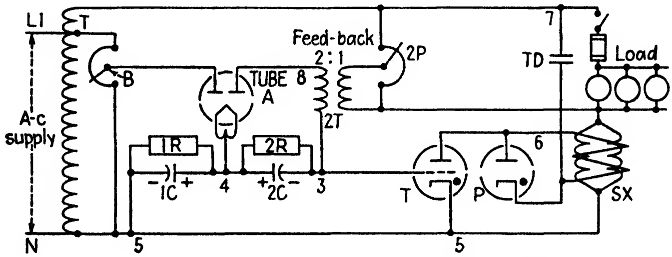


FIG. 14D.—Circuit for dimming theater lights

which we reach Fig. 14H, where tubes 3 and 4 operate like tubes T and P of Fig. 14D.

14-4. Phanotrons in A-c Inductive Circuits.—If a single phanotron and an inductive load X are connected across the a-c supply, as shown in Fig. 14E, a small wave of current A flows for most of each cycle. Notice that this tube-1 current flows during both the positive and the negative half cycles of the a-c supply, yet

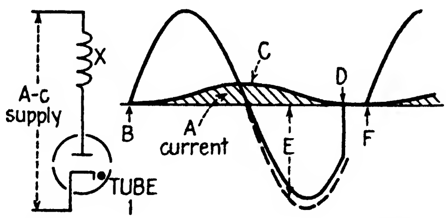


FIG. 14E. Action of single phanotron in inductive circuit.

we know that this current flows only in one direction; this occurs only because the load is inductive and stores energy. Current begins to flow at B. Since the inductive load prevents rapid changes of current (as a flywheel prevents changes of speed) the tube-1 current increases only to C before the supply voltage reverses. However, this current flowing in X has stored energy in X; this energy must escape before the current can stop. To

keep the current flowing through tube 1, the X energy produces a voltage E, which is positive at the X terminal nearest the tube anode; this X voltage keeps the anode 15 volts more positive than the cathode. Current continues to flow through tube 1 until the energy has drained out of X, at point D. At the start of the next half cycle at F, a similar wave of current begins.

If now another phanotron is added (tube 2 in Fig. 14F), notice how the current through tube 1 and X continues to increase, cycle after cycle, until the amount of current is limited only by the d-c resistance of X. Tube 2 is connected opposite to tube 1—any current flowing in one tube cannot flow at the same instant in the other tube. Electrons from the a-c line flow from 5 through tube 1 and X to 7 during each positive half cycle. At

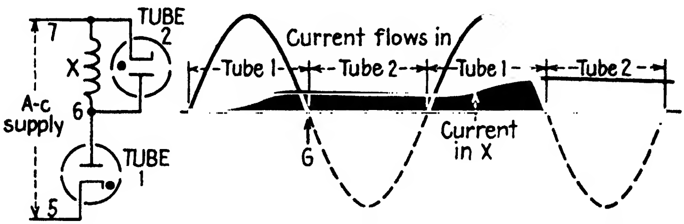


FIG. 14F. Two phanotrons permit greater current flow in X.

G, when the supply voltage reverses, reactor X generates a voltage (as it did in Fig. 14E) that is positive at the X terminal 6. This X voltage forces electrons to flow from 7 through tube 2 to 6; notice that these electrons flow through X in the same direction, whether they flow also through tube 1 or through tube 2. Since tube 2 permits this X current to flow unchecked during the negative half cycles, the amount of direct current increases—each positive half cycle raises it higher. The final amount of direct current in Fig. 14F may be many times greater than the size of the current pulses in Fig. 14E.

14-5. A Thyratron and a Phanotron in an A-c Inductive Circuit.*—To show the effect in an inductive circuit when we delay the firing point of a tube, Fig. 14G uses a thyratron 3. If the a-c grid voltage (from transformer T) fires tube 3 near the beginning of the half cycle, the result is as shown in Fig. 14E.

However, if tube 3 is fired late in the half cycle, as at J in Fig. 14G, the tube current increases slowly, rises only to K and stops

* See also Sec. 15-12.

at L. Supply voltage is connected across X during the interval M. The action of X is the same as before, until the energy has drained out of X.

In Fig. 14H, a phanotron tube 4 is added across X. If thyratron 3 is fired early in the half cycle, Fig. 14F shows that the supply voltage appears across X nearly half the total time, so a

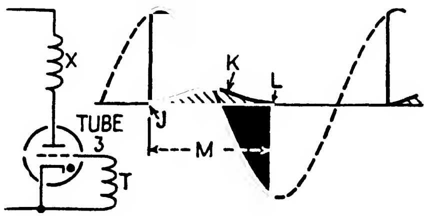


FIG. 14G.—Action of a thyratron in inductive circuit.

large current flows. However, when tube 3 is fired late, as at N in Fig. 14H, the current increases in X during only the brief intervals P. During the longer intervals Q, tube 4 passes current; this current decreases slowly, owing to the small heat loss in this circuit. The final amount of direct current (Fig. 14H) is less than the direct current in Fig. 14F, because the firing point of thyratron 3 is delayed.

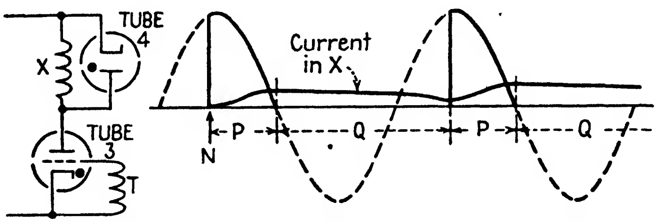


FIG. 14H.—With an added phanotron, thyratron 3 controls current in X.

14-6. Thyratron Grid Circuit for Reactor Control.—In Fig. 14D, tubes T and P control the amount of direct current in the d-c winding of saturable reactor SX (like tubes 3 and 4, described above). These vapor-filled tubes are protected by the 5-minute time-delay contact; after this TD contact closes, anode current flows in tubes T and P only when the grid of T permits.

The grid circuit of T includes only the two voltages across capacitors 1C and 2C; both of these capacitors are charged by current flowing through rectifier tube A. During the half cycle

when slider B is more positive than N or 5, electrons flow from 5 through $1R$, cathode to left-hand anode of tube A, to B; this flow charges $1C$ so that it is positive on the side toward the thyratron-T grid. Similarly, the a-c voltage of the feed-back transformer $2T$ (center of Fig. 14D) forces electrons from its terminal 3 through $2R$, and cathode to right-hand anode of tube A; this flow charges $2C$ so that it is negative on the side toward the thyratron-T grid. Therefore, the $2C$ voltage opposes the $1C$ voltage; the $1C$ voltage tries to let thyratron T pass current, so it is a "turn-on" voltage; across $2C$ is a "turn-off" voltage.

Figure 14I shows these voltages in the grid circuit of thyratron T. Slider B (of Fig. 14D) is turned to the upper end so that full a-c supply voltage ($L1$ to N) is applied across tube A and $1R$ in series; in this position, the voltage at slider B "tells" the control circuit to keep the lamps "full on," or brightly lighted. This voltage B to N (shown in Fig. 14I) charges capacitor $1C$, which loses very little of this voltage before the next flow of tube A current recharges it.* By itself, this $1C$ voltage would keep the grid of thyratron T positive at all times.

Meanwhile, capacitor $2C$ in Fig. 14D is being charged once each cycle by the a-c voltage 3-to-8 of the secondary of $2T$, the feed-back transformer. The adjuster $2P$ is turned to its upper end, so that the entire voltage across the lamp load is also applied to the primary of $2T$. This transformer has a 2-to-1 ratio the 3-to-8 voltage is twice the primary or lamp voltage and is shown in Fig. 14I. Although capacitor $2C$ is charged by this large voltage, $2C$ loses most of this charge within a half cycle (for $2R$ has less ohms than $1R$, and the time constant of $2C$ and $2R$ is about $1/100$ sec). By itself, this $2C$ voltage would keep the grid of thyratron T negative at all times.

When the $1C$ voltage and $2C$ voltage are combined in the T grid circuit, the result is found by adding these voltages together in Fig. 14I. The result is curve RSV, which shows the potential at the grid of thyratron T. This T grid potential crosses the cathode line at S, so thyratron T is fired at this point, perhaps 60 deg late in the half cycle of T-anode voltage. The flow of current (forced through the d-c winding of SX by the part cycles of

* The ohms of $1R$ and the microfarads of $1C$ are large so that the time constant[4-5] of this circuit is perhaps several seconds; there is little loss of voltage during one cycle of time.

voltage, as shaded in Fig. 14*I*) is enough to cause the lamps to be medium bright. If greater brightness is wanted (at this highest setting of slider *B*), the slider of 2*P* may be turned clockwise; only a part of the lamp voltage is now applied to 2*T*, so the 3-to-8 voltage decreases. The new 2*C* voltage is shown by the broken line *UX* in Fig. 14*I*. This smaller 2*C* voltage (combined with the unchanged 1*C* voltage) cannot keep the *T* grid negative later than *W*, so tube *T* is fired nearer the start of the half cycle. This increases the average amount of direct current in *SX* and applies greater voltage to the lamps. In this way, 2*P* selects the highest lamp voltage or greatest brightness desired.

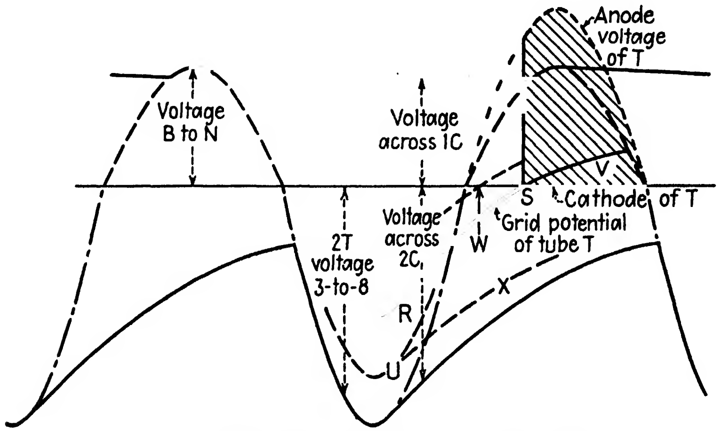


FIG. 14*I*.—Waveshapes in the circuit of Fig. 14*D*.

14-7. Dimming the Lamps.—To dim the lamps, the lever *B* in Fig. 14*D* is moved downward. This decreases the a-c voltage *B*-to-*N*; capacitor 1*C* discharges through 1*R* until its charge is equal to this lower voltage, as shown in Fig. 14*J*. The left-hand cycle in Fig. 14*J* shows bright-light conditions, with thyratron *T* being fired at *W*, very early in the half cycle of anode voltage. About ½ sec after lever *B* is moved downward, there is much less voltage across 1*C*; however, the lamp voltage has decreased very little, so the feed-back voltage 3-to-8 is still large. The sum of the 1*C* and 2*C* voltages produces a grid-voltage curve *EF*, which fires thyratron *T* quite late, at *F*. The current in the d-c winding of *SX* is permitted to decrease, so the lamp voltage decreases further. The right-hand part of Fig. 14*J* shows the final result; the 3-to-8 voltage has decreased and 2*C* has less voltage. The

new grid-voltage curve *GH* lets thyratron *T* pass current at *H*; the resulting current is just enough to make *SX* apply the desired lower voltage across the lamps so that they are not so bright.

At any setting of the lever *B* in Fig. 14*D*, this circuit holds steady lamp voltage and brightness, although the number of lamps may be changed. Suppose half of the lamps are removed from this circuit. With less lamp current flowing through the a-c winding of *SX*, there is less voltage drop across *SX*, more voltage across the remaining lamps. However, as this lamp voltage starts to increase, the 3-to-8 voltage of 2*T* also increases. Capacitor 2*C* becomes charged to a higher voltage (but the 1*C*

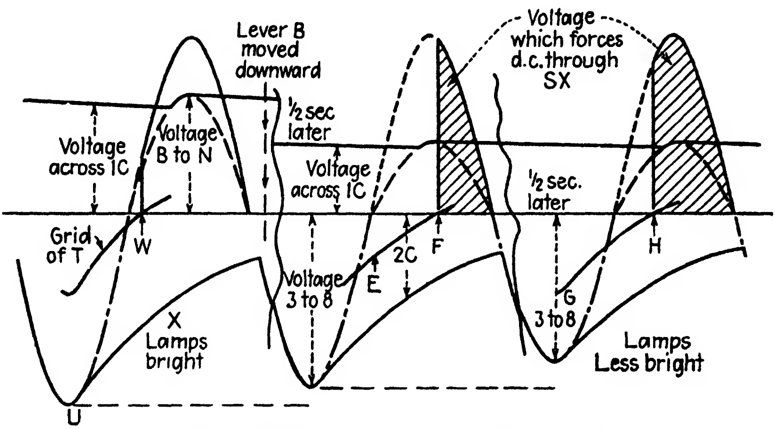


FIG. 14*J* – Changing waveshapes to dim the lamps.

voltage remains unchanged); the sum of the 1*C* and 2*C* voltages crosses the cathode line later, so thyratron *T* is fired later. Less current flows in the d-c winding of *SX*, so its inductance increases, causing greater voltage drop across *SX* and bringing the lamp voltage back to normal.

A rise in a-c supply voltage tries to increase the brightness of the lamps. Again, this increased lamp voltage increases the 3-to-8 and 2*C* voltages, phasing back thyratron *T*; the lamp voltage and brightness are held at the desired level.

14-8. Reactrol Heating Control (CR7508-A109).—As the voltage of a large group of lamps is controlled in Fig. 14*D*, the circuit of Fig. 14*K* controls the temperature of an electric furnace by gradually changing the voltage across the resistance-type heaters. Most of Fig. 14*K* is the same as Fig. 14*D*, so further

study is needed only of the circuits added at the left-hand side of Fig. 14*K*. Instead of using a simple slider (like *B* in Fig. 14*D*), we control the desired furnace temperature by a voltage signal, which is produced between the sliders of two potentiometers 3*P* and 4*P*.

To measure or respond to the furnace temperature, a separate temperature-control instrument is needed, which is not shown in Fig. 14*K*, except that this instrument contains and operates the slide-wire potentiometer 3*P*. This temperature-control instrument responds to the tiny voltage produced by thermocouple,[28-14] mounted in the furnace. As the furnace temperature rises, the thermocouple produces a larger voltage, which makes the instrument move its slider to a position higher on the slide-wire of 3*P*. While the position of this slider changes only when the furnace tem-

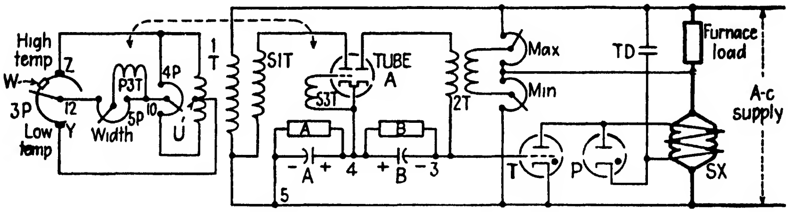


FIG. 14*K* Circuit of Reactrol heating control (CR7508-A109)

perature changes, the whole slide-wire may be turned by hand. In Fig. 14*K*, this slide-wire is shown as nearly a complete circle, at 3*P*; the resistance of this wire is very small, except for a small portion *W* (about 100 ohms). When high furnace temperature is wanted, the slide-wire circle is moved clockwise until *W* is near *Z* (which is the position shown in Fig. 14*K*). The 3*P* slider 12 is touching the slide-wire below the *W* portion, so 12 is at the same potential as the end *Y*. This position "calls for" full heat to raise the furnace temperature. Let us see how this is done.

In this circuit (left-hand part of Fig. 14*K*), transformer 1*T* is the only source of voltage. Only about 8 volts a.c. appear between the two ends of the 1*T* secondary winding, and 4*P* is connected across this voltage. If the slider of 4*P* is at the center of its movement, the potential at this slider 10 is then the same as at mid-point *U*. Notice that 3*P* is connected across one-half of 1*T* secondary, so only 4 volts appear across the 3*P* resistance wire *W*.

When the 3*P* slider is touching below *W* (with slider 10 at the center of 4*P*), points 10 and 12 are at the same potential, so no voltage is applied to transformer 3*T*. The 3*T* secondary winding is in the grid circuit of tube *A*. With no voltage in this grid circuit, the triode, or left-hand part of tube *A*, passes full current; these electrons flow from terminal 5 of 1*T*, through resistor *A*, cathode to anode of the *A* triode, to the upper end of the 1*T* high-voltage secondary. This flow charges capacitor *A* to a large voltage, which, as described in Sec. 14-8, turns on tube *T*, saturates *SX* and applies nearly full line voltage to the furnace heaters.

14-9. Regulating the Furnace Heat.—As the heaters gradually raise the furnace temperature, the temperature-control instrument slowly moves the slider 12 along the slide-wire of 3*P* (upward in Fig. 14*K*), until the slider moves onto the resistance wire *W*. Since *W* has 4 volts more potential at *Z* than at the *Y* end, the movement of slider 12 along *W* slowly increases the a-c voltage between points 12 and 10 If the 5*P* slider is turned so that it touches at 12, all of this small voltage is applied to the 3*T* primary. By the time slider 12 has moved partway across *W*, there is enough voltage (1 to 2 volts) across 3*T* so that the 3*T* secondary voltage makes the tube-*A* grid quite negative during each half cycle when the anode of triode *A* is positive. This decreases the triode-*A* current and reduces the voltage across capacitor *A*; the tube-*T* current decreases and the inductance of *SX* increases, so that only enough voltage is applied to the furnace heaters to keep the furnace at the desired temperature.

A temperature-instrument pointer, which moves when the slide-wire is turned by hand, is set at the desired furnace temperature. After the furnace has reached the resulting steady temperature, a measurement may show that the furnace is hotter or colder than the pointer indicates. To decrease this error, "Position Adjustment" 4*P* may be moved.

When "Width Adjustment" 5*P* connects the 3*T* primary across the whole 12-to-10 voltage, the 3*P* instrument slider needs to move only a small part of the distance across *W* to change the furnace heaters from "full on" to "full off"; this controls the furnace within a narrow temperature range or width. To let the furnace temperature swing between wider limits, 5*P* is turned so that only part of the 12-to-10 voltage reaches 3*T*. Now the

instrument slider of 3*P* must be moved farther across *W*, to give the change from "full on" to "full off."

When the hand pointer and slide-wire 3*P* are turned to a lower desired temperature, the slider 12 now touches above *W*, at the same potential as *Z*. The entire voltage *Z*-to-10 is available to make the 3*T* secondary voltage drive the tube-*A* grid negative; tube *T* is turned off, *SX* has its greatest impedance or choke effect, and the heaters are nearly shut off until the furnace cools down. When the temperature-control instrument moves slider 12 partway down across *W*, the 3*T* voltage decreases enough to turn on triode *A* partly, giving just enough voltage at the heaters to hold the furnace temperature at this lower setting.

Questions

True or false? Explain why.

1. In Fig. 14*B*, if one tube fails or is removed, all battery charging stops.

2. A saturable reactor is an amplifier.

3. If a stiffer spring is used above *CR* in Fig. 14*B*, the battery may be overcharged.

4. The circuit of Fig. 14*D* will not work if point 7 is connected to *L*1 (so that the upper part of autotransformer *T* is not used).

5. In Fig. 14*D*, the circuit works if potentiometer *B* is connected across a d-c voltage instead of across transformer *T*.

6. A saturable reactor produces no output voltage from its a-c winding.

7. If the tube-*A* filament burns open (Fig. 14*D*), the lights become brighter. (Assume tube *T* is a negative-grid-control tube.[11-2])

8. If too many lights are turned on (in the load circuit of Fig. 14*D*), tubes *T* and *P* may be overloaded.

9. If the 2*T* terminals 3 and 8 become reversed (Fig. 14*D*), the lights turn off.

10. If a total of 2 amperes flows through tubes 1 and 2 in Fig. 14*F*, then the tube-1 current is 1 ampere if tube 2 is removed.

11. If resistor *B* burns open in Fig. 14*K*, the furnace cools.

CHAPTER 15

TUBE CONTROL OF A D-C MOTOR

The tube circuits studied this far are used to control equipments that have little or no movement. Electric motors also are controlled by tubes; such tube circuits are often used with d-c motors, to give gradual and accurate control of the motor speed.

15-1. The D-c Shunt Motor.—For use with electron tubes, the d-c motor has electrical parts as shown in Fig. 15*A*. The part that moves or rotates is the armature, whose current-carrying windings are connected to a part of the armature called a commutator, made of many copper bars shaped into a cylinder. The smooth, curved surface of the commutator slides beneath carbon brushes; through these brushes the direct current flows into or out of the armature. The d-c motor has one or more field windings in its frame; a series field winding uses the same current as the armature, but the shunt field has a flow of current separate from the armature.

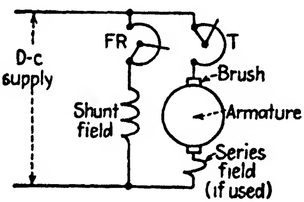


FIG. 15*A*.—Connections and parts of a d-c shunt motor.

To increase the speed of the d-c motor, the voltage across the armature must be increased, or the voltage across the shunt field must be decreased. A field rheostat (*FR* in Fig. 15*A*) is often used for speed control; however, when the armature voltage is reduced by a rheostat *T*, a change in motor load also causes a change in speed. (A greater load increases the armature current and causes greater voltage drop across the resistance of *T*; this reduces the voltage across the armature, so the speed decreases.) This effect of load on speed is avoided if the armature is connected directly to a d-c supply whose voltage can be carefully controlled; such a supply may be a separate d-c generator whose voltage is varied by changing the generator field current. Similar results are obtained by using tubes, as will be shown later.

15-2. Armature Control and Field Control of Motor Speed.—The speed of a d-c motor is controlled through a wide range by changing both the armature voltage and the field voltage, as is shown in Fig. 15*B*. When the armature is connected across the largest voltage that the motor can stand continuously (called its *rated voltage*), and the field current is also at its largest or rated amount, the fully loaded motor runs at a medium speed, called its *base speed*. Figure 15*C* shows the usual way of operating a motor below or above its base speed; in this example, the base speed is 1750 rpm (revolutions per minute). At point *A* in Fig. 15*C*, notice that the armature voltage and field voltage are both at their largest amounts (250 volts), and this is at base speed. To reduce the speed, the field remains unchanged but the armature voltage is reduced (by lowering the d-c supply voltage). To make the motor run faster than base speed, the armature voltage is kept at 250 volts but the field voltage (and current) is reduced, by turning rheostat *FR* (clockwise) to increase its resistance. If the field current is decreased too far, the motor speed increases above a safe amount (as above point *B* in the example of Fig. 15*C*).

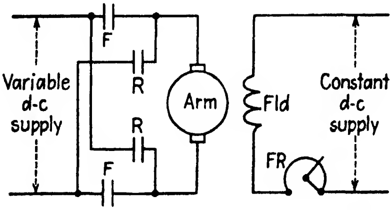


FIG. 15*B*. Reversing armature control and separate adjustable field

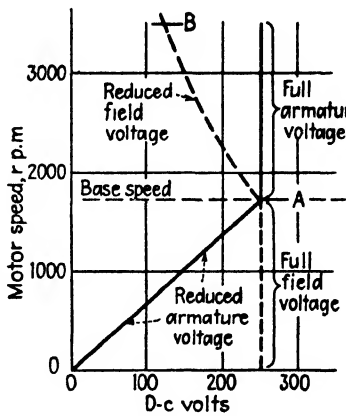


FIG. 15*C*. D-c motor operation above and below base speed.

The d-c motor is usually started with full field voltage, but with reduced armature voltage, so as to decrease the inrush or starting current.

To reverse the direction in which a d-c motor turns, the connections to either the field or the armature may be reversed. In Fig. 15*B*, the motor runs "forward" when contacts *F* are closed, or runs "reverse" when contacts *R* are closed.

15-3. Rectified Current for a D-c Motor.—To get a supply of direct current for the d-c motor, simple rectifiers (without grid control) are sometimes used, as in Fig. 15*D*. (Often both the armature and the field are supplied from a single rectifier.) These tubes change the a-c supply into pulsating d.c., but cannot control the amount of the d-c voltage; therefore, the anode transformer must furnish the correct a-c secondary voltage, which, after passing through the tubes, will become the desired amount of d-c voltage. In Fig. 15*D*, the field voltage (and current) is reduced by rheostat *FR* to increase the motor speed; full armature voltage is used, except when starting the motor from rest. If contacts *M* and *S* both close while the motor is at standstill, (*a*) in Fig. 15*E* shows the large armature current (solid line) that flows, perhaps hurting the commutator. However, if contact *S* remains open, the resistor *R* reduces the starting current, as

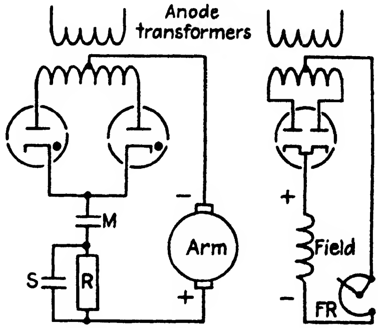


FIG. 15*D*.—D-c motor operation from simple rectifiers.

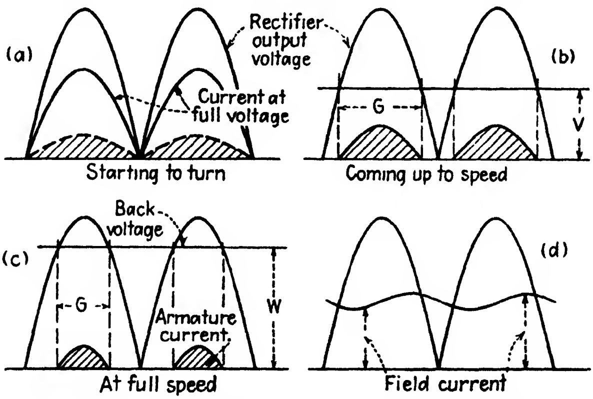


FIG. 15*E*. - Waveshapes in motor circuit of Fig. 15*D*.

shown by the dotted line in (*a*). Notice that, just as the motor starts to turn, the rectifier output voltage forces current to flow in the motor armature during each entire half cycle of a-c supply.

As its speed increases, the motor produces a d-c voltage of its own (shown at V and W in Fig. 15E, and called the motor's *back voltage* or counter emf). Because this back voltage opposes the rectifier-output voltage, current flows in the armature only during the portions G, while the rectifier voltage wave is higher than V or W. At medium speed, (b) in Fig. 15E shows that the armature current flows in pulses, each about a quarter cycle long and of medium size or height. At full speed, (c) shows that the back voltage is so large (at W) that the armature current flows in very short pulses, small in height.*

Meanwhile, the motor operates with full field current; as shown in (d) of Fig. 15E, this current is nearly constant during each cycle, for the large inductance of the field winding prevents much change of current.

15-4. Thyratron Control of Reeling Tension.—In Fig. 15F, a d-c motor turns a reel on which a strip of soft material is being

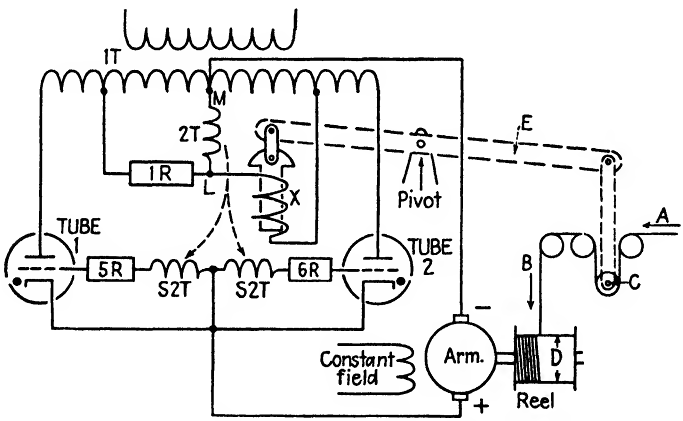


FIG. 15F.—Tube control of winding tension.

wound; at A this material comes at constant speed. As more material is added on the reel and its diameter D increases, the motor speed must decrease gradually or the reel begins to wind the material faster than it is fed in at A. Tubes 1 and 2 are grid-controlled, to change the armature voltage of the motor,

* These current pulses appear also in Fig. 14C, because a battery has a back voltage (like a running d-c motor) that prevents current from flowing except during a small part of the rectified a-c voltage wave.

thereby changing the motor speed; meanwhile, the motor field current (from another d-c supply) is left unchanged.

This circuit tries to hold steady tension or pull at *B*. At *C* a roll rides in a loop of the material; since the weight of *C* is constant, it gives a steady stretch or pull on the strip of material. If the motor turns too fast, the material at *B* moves faster than at *A*, and the *C* roll is raised; this upward movement of *C* decreases the motor speed, as explained below. If the motor slows down too much, the material lowers the *C* roll, and this increases the motor speed.

In Fig. 15*F*, the transformer 1*T* supplies anode voltage to thyratron tubes 1 and 2; if these tubes let the whole voltage wave pass through (like the phanotrons in Fig. 15*D*), the rectified voltage across the motor armature is so great that the motor speed is too high. By phase-shift control,[13-1], these tubes may be made to fire later during each cycle of a-c power supply; the voltage across the motor armature may now be so low that the motor speed is too low. Let us see how the movement of the *C* roll is made to give a signal to the thyratron grids, so that the average motor speed will remain just right.*

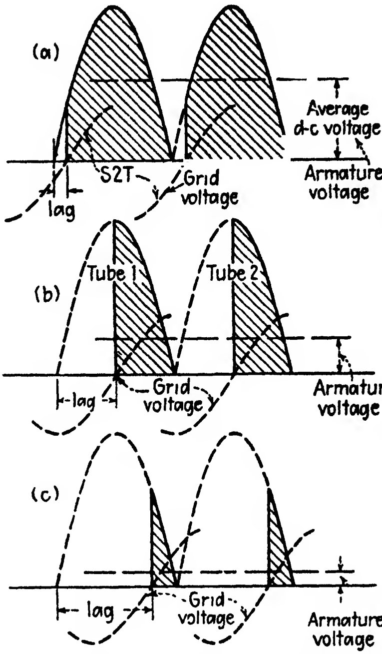


FIG. 15*G*.— Armature-voltage waveshapes in Fig. 15*F*.

When the *C* roll is lowered, the lever *E* pulls the plunger of solenoid *X* farther out of the solenoid coil; this decreases the amount of inductance in *X*. This solenoid, together with resistor 1*R*, forms a phase-shifting bridge (as described in Sec. 13-7 and Fig. 13*H*).

* Such an arrangement, where the operation (or change of tension) causes a mechanical movement or change in the speed-control circuit, is called a *mechanical feedback.*

As this inductance in X decreases, the voltage applied to transformer $2T$ becomes more nearly in phase with the voltage of $1T$; each of the two secondary windings $S2T$ therefore fires its tube earlier in the half cycle. If the C roll reaches its bottom position, the plunger of X is withdrawn so far that a large d-c voltage reaches the motor armature, as shown in (a) of Fig. 15G; the motor runs at full speed, raising the C roll. If the C roll reaches its top position, the plunger is now fully inserted; the increased inductance of X makes the tubes fire late in the half cycle, so only a small d-c voltage reaches the motor armature, as shown in (c) of Fig. 15G; the motor slows down. The C roll rarely reaches either of these extreme positions; probably it "floats" near the middle position, so that the plunger of X is partly withdrawn. The medium d-c voltage shown in (b) runs the motor at about the right speed; a slight movement of the C roll changes the motor speed until the roll is back in its middle position.

Notice how Fig. 15G shows that, to phase-shift or delay the firing of the tubes, we move the entire curve of a-c grid voltage to the right; the size of this a-c grid voltage does not change, and it is the only voltage in the tube grid circuit.

15-5. Phase Shifting with a D-c Signal Voltage.—The circuit of Fig. 15H shows another way to phase-shift thyratron tubes; here the amount of d-c voltage across the motor armature is controlled or changed by moving the slider S on resistor $3R$. Transformer $1T$ supplies a-c voltage to the anodes of thyratron tubes 3 and 4; a part of this $1T$ voltage is used also for the phase-shifting bridge[13-7] of $1R$ and $1C$. No part of this bridge circuit is variable; as described in Sec. 13-5, this 25,000-ohm resistor and 0.1 mu f capacitor are of the right sizes so that the voltage across $1R$ is about 45 deg out of phase with the $1T$ voltage, or the voltage M-to-L is about 90 deg out of phase with $1T$. Since this M-to-L voltage is applied to transformer $2T$, each $2T$ secondary winding supplies an a-c voltage that lags 90 degrees behind the tube anode voltage at all times. But this a-c voltage perhaps is not the only voltage in this grid circuit.

In Fig. 15H, to see what grid voltage controls tube 3, we must include all voltages between grid G and cathode K; there is the 35-volt a-c secondary winding of $2T$ and also the d-c voltage between the $3R$ slider S and point K, where the two batteries are

connected together. Since each battery supplies 50 volts,* the mid-point of resistor $3R$ is at the same potential as K. When slider S is at this mid-point, there is no d-c voltage included in the grid voltage of tube 3; the result is shown at (*a*) in Fig. 15*I*. Here the a-c wave of secondary voltage ($S2T$) lags about 90 degrees and fires tube 3 at point P; the tubes apply voltage to the motor armature for a half of each half cycle. Notice that the crest, or top, of this grid-voltage wave occurs on the line Y-to-Z.

If we now move slider S to the left on $3R$, S becomes more positive than K; the d-c voltage between S and K raises the whole

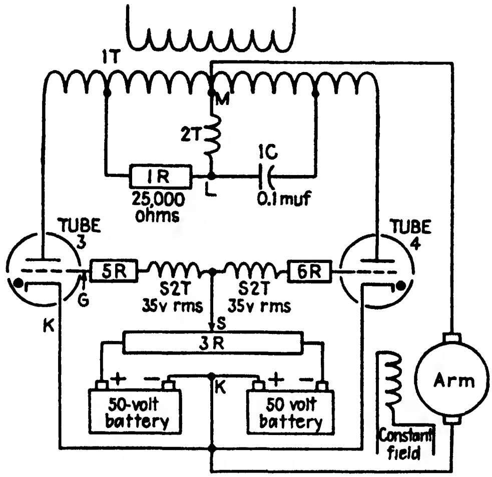


FIG. 15*H* Phase-shift control of thyratrons by a d-c grid voltage

curve of grid voltage, until it reaches the position shown in (*b*) of Fig. 15*I*. Notice that the shape and the size of the a-c curve of grid potential have not changed, neither has the curve moved to the left or to the right, for the crest is still on line Y-to-Z. However, when the 50 volts d.c. (between S and K) raises this a-c curve, point Q is moved to the left, where the a-c grid-potential curve crosses the straight line of cathode potential. Tube 3 now starts to pass current at Q, and voltage is applied to the motor armature during almost all of each cycle, giving large d-c armature voltage and high motor speed.

When S is moved to the right-hand end of $3R$ (in Fig. 15*H*), S

* Few industrial circuits use batteries in the way shown in Fig. 15*H*. These batteries merely serve as constant d-c voltages, to be replaced in later circuits by the constant d-c voltages from other tube-operated circuits

is now 50 volts more negative than K; the whole curve of a-c grid potential is lowered to the position shown in (c) of Fig. 15*I*. Again, there has been no change in shape, size or phase position of the a-c voltage wave from *S2T*; its crest is still on line *Y*-to-*Z*. However, not until point R does the grid potential cross the cathode-potential line to make the grid more positive than the cathode. The tubes fire very late in the half cycle, so the motor armature receives very little d-c voltage and turns at low speed.

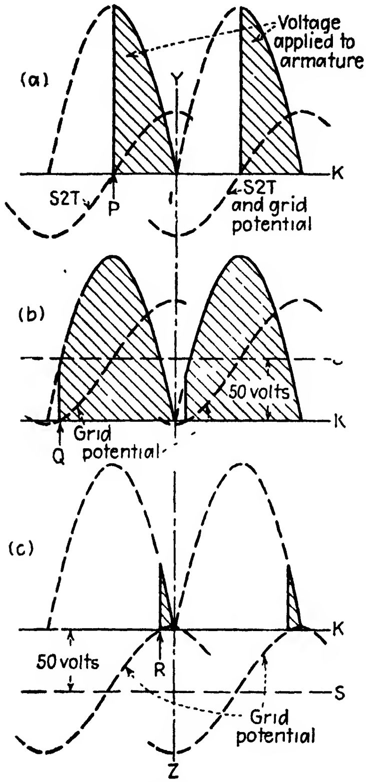


FIG. 15*I*.—Waveshapes in Fig. 15*H* as the d-c grid voltage varies.

From Figs. 15*H* and 15*I*, we see that thyratron tubes may be phase-shifted by changing only the amount of d-c voltage in the grid circuit, while all the a-c voltages remain unchanged; a small-current d-c signal may gradually control the large-current output of vapor-filled tubes.

15-6. Motor Speed Held Constant by Armature Control.—Figure 15*F* showed how a d-c motor's speed is controlled by a mechanical movement (of a roll and solenoid plunger) that is changed into a phase-shifting signal. To hold a steady or constant motor speed, Fig. 15*J* shows how the thyratron tubes 5 and 6 may be phase-shifted by using any change in the d-c voltage across the motor armature.* The field current is constant, so the motor speed increases when the armature voltage increases; the circuit in Fig. 15*J* aims to hold constant voltage across the armature and thereby to prevent a change of speed.

* This arrangement in Fig. 15*J*, where an electrical signal (such as motor armature voltage) is used directly in the speed-control circuit, is called an *electrical feedback*.

Tubes 5 and 6 in Fig. 15*J* are phase-shifted by the same kind of circuit explained above in Fig. 15*H*. Instead of two batteries in the grid circuit, Fig. 15*J* uses one 300-volt battery and uses the motor-armature voltage in place of a second battery. The armature voltage has a ragged waveshape (as shown in Fig. 15*G*), so *X* and 3*C* are added as a filter, so that the voltage across resistor 4*R* is a smooth average of the d-c armature voltage.

To see what grid voltage controls tube 5, trace from its grid through 5*R* and the 35-volt winding *S*2*T*, to slider *S*; across the d-c voltage of 2*R* to point *B*, across the d-c voltage of 4*R* to

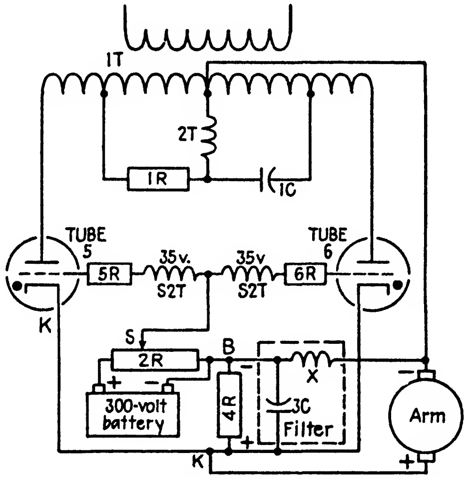


FIG. 15*J*.—Using d-c armature voltage to regulate motor speed.

cathode *K*. Notice that the 2*R* voltage bucks or opposes the 4*R* voltage; if *S* is set so that 150 volts d.c. appears between *S* and *B*, and if the armature voltage makes 150 volts d.c. appear across 4*R*, then one of these voltages offsets the other; only the *S*2*T* a-c voltage remains in the tube-5 grid circuit. As shown in (*a*) of Fig. 15*I*, this a-c grid voltage by itself fires the thyratrons so that voltage is applied across the motor armature for only half of each a-c wave. This half voltage runs the motor at a medium speed and furnishes the 150 volts d.c. across 4*R*.

Suppose that a sudden dip in a-c supply voltage reduces this armature voltage to 100 volts, which lets the motor start to slow down. With only 100 volts across 4*R* (in Fig. 15*J*), the 150 volts between *S* and *B* is now 50 volts greater than the 4*R* voltage, so

the grid potential is raised 50 volts. The result appears in (*b*) of Fig. 15*I*; the whole wave of a-c supply voltage is now applied to the motor armature (after being rectified by tubes 5 and 6). The average d-c armature voltage returns to 150 volts or higher, so the motor does not slow down.* As the voltage across 4*R* also rises toward 150 volts, the 50-volt d-c "boost" in grid voltage decreases to an amount that continues to hold 150 volts across the motor armature.

At this point let us notice that the voltage of the battery (in Fig. 15*J*) does not change even when the a-c supply voltage dips. In any regulating circuit there must be such a voltage, which never changes, but which can act as a "landmark" or point of reference. This d-c voltage from the battery is called the *reference voltage* in this circuit; (the battery may be replaced by any other source of d-c voltage, as long as that voltage remains constant or steady at all times).

In Fig. 15*J*, the slider *S* is moved along 2*R* to select the desired motor speed. If *S* is moved suddenly to the right, decreasing the *S*-to-*B* voltage by, say, 50 volts, the 4*R* voltage is now the larger; it lowers the position of the a-c grid-voltage curve, and the result is shown in (*c*) of Fig. 15*I*. The thyratrons are "phased off," so that very little voltage reaches the motor armature; as the motor speed decreases and there is less d-c voltage across 4*R*, a new operating point is reached where the 4*R* voltage is equal to the *S*-to-*B* voltage. Slider *S* selects the amount of reference voltage *S*-to-*B*; the circuit shifts the firing point of tubes 5 and 6 until the 4*R* voltage is equal to this reference voltage.

15-7. Motor Speed Held Constant by Field Control.—In the circuits of Figs. 15*F*, 15*H* and 15*J*, the tubes control or change the motor-armature voltage. Motors smaller than 10 to 40 hp may be tube-controlled in this way; for larger motors, the required amount of armature current may be greater than suitable tubes†

* The average voltage sets the motor speed. The armature voltage may have any kind of waveshape (as in Fig. 15*I*); the voltage peaks and valleys follow each other too fast to affect the speed—only the average of these peaks and valleys has any affect on speed. However, this waveshape does affect the motor temperature, or heating.

† Thyratrons and phanotrons are the types of tube best suited to supplying rectified current to a d-c motor armature. Because the motor generates a back voltage (so that only 25 to 100 volts remains between the rectifier-

can handle. However, the speed of both small and large motors may be controlled by using tubes in the motor-field circuit. The field current is perhaps $\frac{1}{10}$ to $\frac{1}{40}$ as large as the armature current.

In Fig. 15*K* the field current is controlled so as to prevent changes in motor speed. This circuit is like Fig. 15*J*, except that a tachometer generator[28-1] is added; a separate d-c source supplies the large current for the main motor armature and also furnishes part of the motor-field current, as set by rheostat *R*.

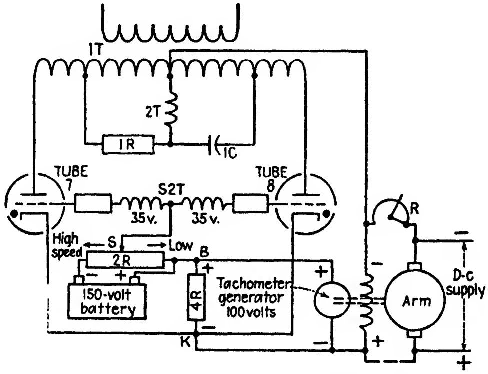


FIG. 15*K*.—Using tachometer voltage and variable field, to regulate speed.

When the motor field receives no current through tubes 7 and 8, enough current flows through *R* to prevent the motor from "running away" or reaching too high a speed.[15-2] Any current flowing through the tubes increases the total field current and decreases the motor speed.

When the motor is not turning, the "tac-generator" voltage is zero; at highest motor speed, the "tac" generates say 100 volts. Since this is a smooth d-c voltage, no filter is needed. Notice that the d-c voltage across 4*R* in Fig. 15*K* is positive at *B* (which is opposite to the 4*R* polarity in Fig. 15*J*). Therefore, the voltage across 2*R* has been reversed also, so that these two d-c voltages buck. The slider *S* is moved to select the desired motor speed. If the *S*-to-*B* reference voltage is 50 volts, tubes 7 and 8 are feeding enough current to the motor field so that the motor

tube anode and cathode) ignitron tubes are not suitable for d-c motor-armature circuits unless the ignitrons have separate high-voltage ignitor circuits and "keep-alive" anode circuits, as described in Sec. 18-8.

operates at medium speed; at this speed, if the "tac" generates about 50 volts also, then only the a-c voltage of *S2T* remains in the grid circuit, as in (*a*) of Fig. 15*I*.

If any load or voltage change makes the motor speed rise, the 4*R* voltage also rises. Since the 4*R* voltage is now greater than the reference voltage *S*-to-*B*, the a-c wave of grid voltage is raised to a higher position, where it fires tubes 7 and 8 earlier in each half cycle. The increased tube current strengthens the motor field so that the motor speed decreases to normal.

Figure 15*L* shows the voltages in the grid circuit (of tube 7 or 8 in Fig. 15*K*) for three positions of slider *S*.

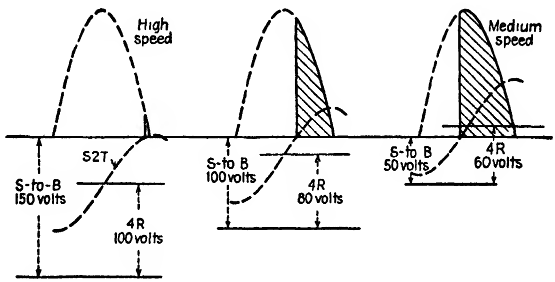


FIG. 15*L*.—Waveshapes in Fig. 15*K*.

15-8. Electronic Motor Control—Weltronic Type Y.—To control the motor speed through a wide range, both the armature and field voltage may be changed. One kind of circuit for such a complete motor control is shown* in Fig. 15*M*; taking power from a-c supply lines, this equipment changes the motor speed when a small dial is turned. At any dial setting, the motor is started and brought to the desired speed merely by pushing a button; the motor remains at this speed, although the a-c supply voltage or the motor load may change.

To keep a more simple circuit, many parts of the complete equipment are left out of Fig. 15*M*, as will be mentioned later. In the diagram shown, the motor-field circuit fills the right-hand portion; we shall see that the field current is controlled in much the same way as in Fig. 15*K*, described above. The field current is supplied through tubes 3 and 4, which are grid-controlled. In contrast, notice that there are no grids in tubes 1 and 2, which

* Other circuits for wide-speed-range motor control are described in Chaps. 24 and 25.

supply current to the motor armature. (Here electrons flow from the center tap of the secondary of $1T$, to 9, through the armature to N, then from cathode-to-anode of tubes 1 and 2.) Although these tubes pass current during the whole a-c wave, the amount of the d-c voltage across the armature is changed by varying the amount of a-c voltage applied (13-to-14) across the primary of transformer $1T$. (This is like the battery-charging circuit described in Sec. 14-2.)

In the upper part of Fig. 15M, notice that transformers $1T$ and $2T$ are connected in series across the a-c supply voltage 5-to-6. These transformers are not energized while contactor M is open. To start the motor, a push-button circuit (not shown) picks up M, whose contacts close next to $2T$, and also next to $1T$.

Transformer $2T$ is the part that controls the a-c voltage across $1T$, and therefore controls the d-c armature voltage. To explain this action, Fig. 15N shows these transformers with the secondary winding of $2T$ connected across a variable resistance R. When all of R is in circuit, the secondary voltage of $2T$ can force very little current A to flow through R and the secondary winding of $2T$. In this condition, $2T$ has very large inductance or choke effect—most of the a-c supply voltage appears across $2T$, very little across $1T$. When the resistance of R is decreased, more current may flow at A, and this decreases the inductance of $2T$—less a-c voltage appears across $2T$, more across $1T$. When R is shorted, the inductance of $2T$ is so small that nearly all of the a-c supply voltage now appears across $1T$.

In Fig. 15M, we see that tube 5 acts in the place of R just described. When tube 5 passes little or no current, this is like large resistance in R, so the a-c voltage across $1T$ is small, and the motor-armature voltage is small. By increasing the tube-5 current, we increase the $1T$ voltage and the armature voltage.* Since tube 5 is a thyratron, we cannot gradually increase the amount of its anode current except by phase-shift control of its grid circuit. This phase-shifting is done by the bridge circuit of $7T$, $7R$ and saturable reactor $6T$, as described later.[16-4] For now,

* Transformer $2T$ has a higher voltage secondary winding (1200 volts) so that tube 5 needs to carry less current. The tube-5 current flows during less than half of each cycle; the unbalanced effect on the a-c voltage across $1T$ is offset by locating the center tap of the $1T$ secondary winding a little away from the true center.

it is enough to know that, when tube 8 (lower center of Fig. 15*M*) increases the amount of current flowing in the d-c winding of reactor 6*T*, this increases the amount of tube-5 current; this increases the amount of motor-armature voltage. Briefly, when tube-8 current increases, the armature voltage increases; so let us see what controls tube 8.

15-9. Direct-coupled Amplifiers.—Tubes 7 and 8 in Fig. 15*M* are connected as a two-stage amplifier—that is, a signal at the grid of tube 7 (first stage) makes a stronger signal appear at the

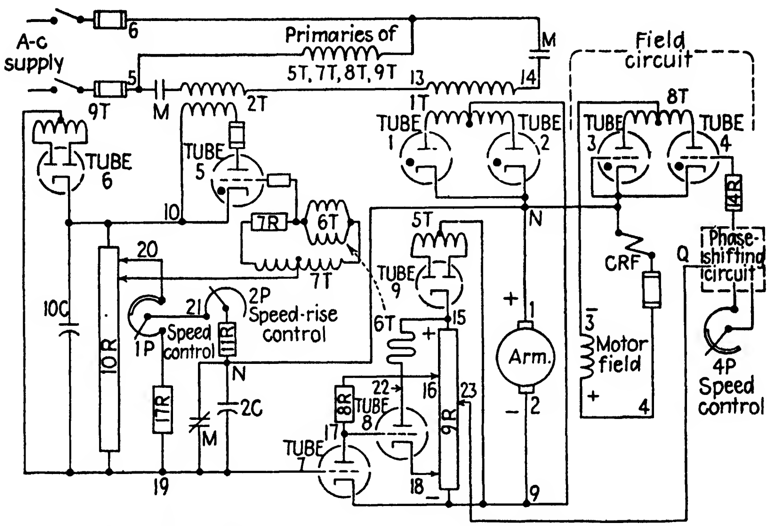


FIG. 15*M*.—Tube control of motor speed—Weltronic type *Y*.

grid of tube 8 (second stage). In this way, the amount of direct current flowing through 6*T* is greatly changed by a very small change of potential at point 19, grid of tube 7.*

Notice how the d-c voltage across resistor 9*R* (at lower center of Fig. 15*M*) supplies the anode circuits of both tubes 7 and 8. At all times, 5*T* and tube 9 produce about 540 volts d.c. across 9*R*, which is positive at its upper end. The second-stage tube 8 and its load 6*T* are connected between points 15 and 18; at lower potentials on 9*R*, points 16 and 9 connect to the first-stage tube 7 and its anode load resistor 8*R*. Each of these tubes is an

* Tubes 7 and 8 are shown as triodes in Fig. 15*M*; they are really beam power tubes,[7-10] but their screen grids and deflecting plates are not shown. The circuit operation is understood without these added parts.

amplifier; they are said to be *direct-coupled,* since the voltage that appears across the resistance of 8*R* is not only the output voltage of the first tube 7, but it also controls the input or grid voltage of the second tube 8—tube 8 is "coupled" to tube 7 by the voltage across resistance 8*R*. If the cathode 9 of tube 7 becomes more negative and increases the flow of tube-7 anode current, there is greater electron flow from point 9 through tube 7 and 8*R* to point 16; the voltage drop across 8*R* increases. Since the potential at 16 cannot change, this greater 8*R* drop lowers the potential at 17; this lowers the grid potential of tube 8, decreasing the amount of electrons flowing from point 18 through tube 8 and 6*T* to point 15.

In such a direct-coupled-amplifier circuit (in Fig. 15*M*), notice these points:

1. When current increases in the first tube 7, current decreases in the second tube 8.

2. For each amount of steady grid voltage at the first tube 7, there is a certain fixed amount of grid voltage at the second tube 8. (In contrast, when two amplifiers are capacitor-coupled,[21-3] the grid of the second tube remains at a low potential except when the first-tube grid potential is rapidly falling.)

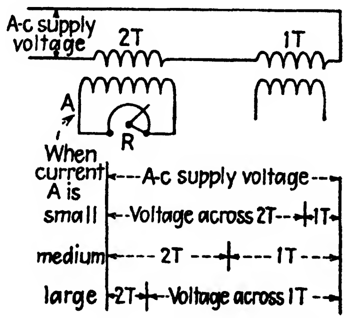


FIG. 15*N*.—Turning *R* changes inductance of 2*T* and the voltage across 1*T*.

3. The second-tube grid (point 17) cannot become more negative than its cathode 18, unless the first-tube cathode (point 9) is quite more negative than 18. If the cathodes of tubes 7 and 8 were connected together, the tube-8 grid voltage would be always positive and could not greatly decrease the tube-8 anode current.

Adding tubes 7 and 8 to the armature-voltage-control circuit of Fig. 15*M*, we see that the armature voltage decreases when the tube-7 grid voltage (from grid 19 to cathode 9) increases the tube-7 anode current. As tube 7 "turns on," tube 8 decreases the d.c. in 6*T* so that the tube-5 current decreases; the a-c voltage decreases across 1*T*, so that the d-c voltage across the motor armature decreases.

15-10. Weltronic Motor-control Operation.—Suppose that the 230-volt motor in Fig. 15*M* is running below medium speed, with about 150 volts d.c. across the armature. This armature voltage makes point 9 (at bottom of Fig. 15*M*, and at the cathode of tube 7) 150 volts more negative than *N*, which is the connection between the field, armature and armature-control circuits. Point *N* is now also at the same potential as 21, the slider of 1*P*, whose dial has been turned by hand to select the desired motor speed.*

At this speed, the slider of 1*P* is below middle position, so there is perhaps a 160-volt drop between slider 21 and point 19. This makes the grid of tube 7 160 volts more negative than *N*, while the armature voltage makes the tube-7 cathode 150 volts more negative than *N*; therefore, the tube-7 grid 19 is only 10 volts more negative than the cathode 9, and tube 7 is passing enough current to let the motor armature receive 150 volts. If a dip in a-c supply voltage decreases the 1*T* voltage so that the motor armature receives only 140 volts d.c., this raises the potential of cathode 9 so that it is 10 volts closer to *N*. This decreases the anode current of tube 7 which (as is explained above in Secs. 15-8 and 15-9) increases the d-c armature voltage so that the motor speed is not affected by this a-c voltage dip.

Let us watch the circuit work while the motor starts and comes up to this medium speed. Before the push button picks up contactor *M*, a normally-closed *M* contact (lower left in Fig. 15*M*) connects points *N* and 19 and shorts capacitor 2*C*. (The voltage between slider 21 and point 19 now appears across the resistance of 2*P* and 11*R*.) The grid of tube 7 is now at *N* potential; also, just at the instant when *M* closes its contacts in the motor-armature circuit, there is no armature voltage, so cathode 9 of

* If very low speed is wanted, 1*P* is turned so that its slider is at the bottom end next to 17*R*. To run the motor at base speed, the 1*P* slider is in its middle position; the upper half of 1*P* has no resistance, so the middle position gives point 21 the same potential as point 20 (20 is a slider on resistor 10*R*, which is adjusted so that the highest armature voltage is not above 230 volts). The d-c voltage across 10*R* comes from 9*T* and tube 6, and is filtered by 10*C*. Turning 1*P* above the middle position makes no greater motor-armature voltage; however, mounted on the same shaft with 1*P*, the same dial also turns 4*P* (right-hand side of Fig. 15*M*), which decreases the field voltage to cause higher motor speed. Below the middle position, 4*P* gives full field voltage.

tube 7 is also at N potential. Since there is zero grid voltage (between grid and cathode of tube 7), the anode current of tube 7 is large; the a-c voltage across $1T$ and the d-c voltage across the armature are both very small, just after M operates its contacts.

Capacitor $2C$ decreases the amount of motor-starting current; without $2C$, point 19 (grid of tube 7) drops suddenly 160 volts below N, shutting off all tube-7 current and applying full d-c voltage to the armature. However, with $2C$ in use, the grid potential of tube 7 cannot drop suddenly; the voltage between N and 19 increases gradually as capacitor $2C$ is charged by electrons flowing from 19 into $2C$, and from $2C$ through $11R$ and $2P$ to point 21. The amount of resistance used in $11R$ and $2P$ controls the speed with which $2C$ charges,* so the slider of $2C$ is set for the desired time delay while the motor speed rises. As the speed rises, the voltage across the armature increases so that point 9 becomes more negative (than N) about as fast as $2C$ lets 19 become more negative (than N); the tube-7 current does not change suddenly, but gradually increases the armature voltage until the motor reaches the speed selected by the setting of $1P$.

Other features, which are not shown in Fig. $15M$, but which are usually supplied in this complete motor-control equipment, include the following: reconnection to operate with either 230- or 460-volt a-c supply; a time-delay relay for tube-warming protection; contactors to reverse the motor direction and to provide fast stopping by dynamic braking; automatic speed compensation to hold constant motor speed, although the motor load changes.

15-11. Field-circuit Operation.—While the armature circuit operates as has been described above, the field tubes 3 and 4 (in Fig. $15M$) are passing electrons, which flow from $8T$ mid-tap to 3, through the motor-field winding to 4, through a fuse, a coil of relay CRF, then cathode to anode of tubes 3 and 4. (CRF prevents motor operation unless normal field current is flowing. CRF remains picked up when the field current is decreased by the high-speed settings of $4P$; however, unless both tubes 3 and 4 work properly, there is not enough field current to keep the CRF con-

* The time constant[4-5] of $11R$, $2P$ and $2C$ is variable from ½ to 2 seconds, so that $2C$ may affect the amount of armature current for as much as 3 to 10 seconds.

tact closed; therefore, it opens the "Stop" circuit of the motor, not shown.)

While the motor is coming up to base speed, and whenever the speed dial (1*P* and 4*P*) is below the middle position, tubes 3 and 4 pass current steadily to give full field strength and greatest motor torque. The phase-shifting part of the field circuit (in the rectangle at the right-hand side of Fig. 15*M*) includes an a-c grid-voltage wave, which lags behind the anode voltage of tube 4. As described above,[15-5] this entire a-c wave is raised or lowered by a d-c voltage, which is produced between N (cathode of tube 4) and Q (signal input to the rectangle). Notice that Q is connected to slider 23, which is 230 volts more positive than point 9. While the motor is starting or while its speed is low, the voltage between 9 and N is less than 230 volts. Tracing from the tube-4 grid, through 14*R* and the phase-shifting rectangle to slider 23, then negative 230 volts to 9, and positive less-than-230 volts to N and the tube-4 cathode, we see that N is more negative than point Q. Tubes 3 and 4 pass current for their entire half cycles, until the armature voltage approaches 230 volts; then the a-c grid-voltage wave in the rectangle starts to affect tube 4. If 4*P* is below middle position, this a-c wave fires tube 4 early in its half cycle. When 4*P* is turned above middle position, the decreased resistance of 4*P* delays the phase of the a-c grid-voltage wave so that tube 4 fires later; this decreases the field current and raises the motor speed.

15-12. Phase Control of Two Tubes by One Grid.—As has been just described, the amount of anode current of tubes 3 and 4 (in the motor-field circuit of Fig. 15*M*) may be changed by phase-shifting the grid voltage of tube 4 alone; meanwhile the grid of tube 3 is connected to its cathode, so that tube 3 acts as a phanotron (vapor-filled diode). Such control of two tubes by one grid is used only in an inductive circuit. Somewhat similar action is described in Sec. 14-5 and Fig. 14*H*.

Tubes 3 and 4 of Fig. 15*M* are shown again in Fig. 15*O* as a phanotron and a thyratron. The phanotron tube 3 always passes current during that entire half cycle when its anode is positive; the thyratron current depends on its grid voltage. If thyratron 4 is fired early at A, current flows steadily through each tube in turn, and through the inductive load X; there is little variation

or ripple in the current as shown in (*a*); many cycles may pass before the current rises to the amount shown.

If thyratron 4 is kept from firing (by phase-shift control of its grid) until *C*, part (*b*) of Fig. 150 shows that the current flows through tube 4 during only the ¼ cycle from *C* to *D*; the current transfers to tube 3 at point D. Notice that tube 3 continues

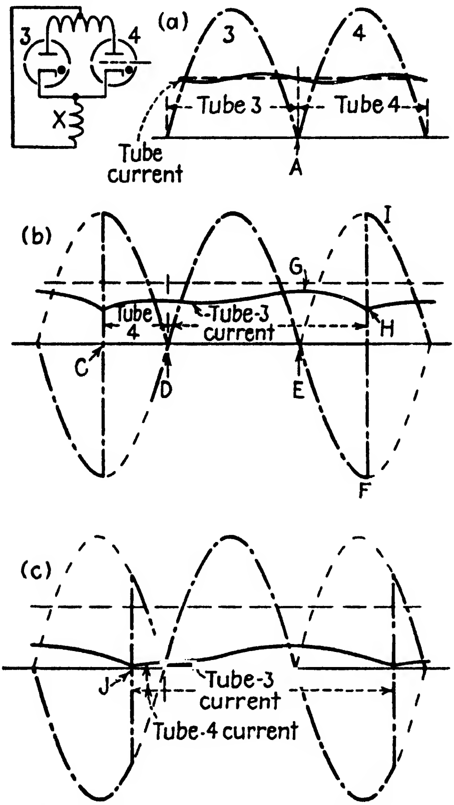


FIG. 150.—Grid control of one tube changes the current through two tubes

to pass current for ¾ cycle, or until tube 4 is again fired; at *E* the voltage across *X* continues to follow the a-c wave of tube-3 anode voltage—this is a negative voltage (from *E* to *F*), which bucks or decreases the current flowing through *X*, so that the amount of this current decreases from *G* to *H*. When tube 4 again fires, the positive voltage at *I* increases the current flow, which may not rise to the full amount before it is again decreased by the delayed

firing of tube 4. The average direct current in (*b*) is less than that in (*a*).

If the firing of tube 4 is further delayed to *J*, part (*c*) shows that the average direct current is much less than before; the result is nearly the same as if the phanotron were being used alone, as shown in Fig. 14*E*.

Questions

1. In Fig. 15*H*, what is the largest voltage that appears across grid resistor 5*R* when slider *S* is at extreme left? At extreme right?

2. In Fig. 15*K*, if the motor-field current is 8 amperes at base speed, and the field current must never become less than 3 amperes, how many amperes (average) must tube 7 carry?

3. In Fig. 15*M*, which devices act as amplifiers that may increase the strength of a voltage signal received at the tube-7 grid, until it is able to change the amount of d-c armature voltage?

4. In Fig. 15*M*, where is the reference voltage for the motor-armature voltage?

True or false? Explain why.

5. In a two-stage, direct-coupled amplifier, the anode current of the second tube rises only when the first-tube-grid signal becomes more negative.

6. A field thyratron is more heavily loaded above base speed than below base speed.

7. A motor armature, supplied through phase-shifted thyratrons, receives a smoother voltage waveshape at high motor speed than at very low motor speed.

The following all refer to Fig. 15*M*.

8. The starting current of the motor is decreased because of electrical feedback.

9. At medium speed, if rectifier tube 9 is removed, the armature voltage decreases. The field voltage increases.

10. The armature voltage has the same waveshape (but of different size) at both high and low speed.

11. The amount of field current has no effect on the amount of voltage across the armature.

12. While the motor comes up to base speed, the voltage across 11*R* and 2*P* is in the tube-7 grid circuit.

13. If 1*P* is suddenly moved from middle position to a lower speed position, 2*C* prevents a sudden increase of tube-7 current.

CHAPTER 16

ARC-WELDING CONTROL

In a way similar to that of the motor drives described in Chap. 14, a d-c motor is used in the automatic control of arc welding; this motor's average speed is varied to give the right size of electric arc to melt the welding rod.

16-1. Arc Welding.—Most arc welding is done by an operator who moves a metal rod or electrode toward the work being welded; he watches the bright electric arc, which slowly melts the metal at the end nearest the work. If he moves the rod too fast, this decreases the length of the arc between the rod and the work. If he holds the rod still, it slowly "burns back"; then the length of the arc increases until the arc "goes out."

The electric power that makes the arc may be a.c. or d.c.; the amount of voltage across the arc (measured between the rod and the work) decreases as the arc length decreases.

When the same shape of work is arc-welded hour after hour, an automatic machine, or welding head, may be used. A tube-operated d-c motor moves the welding rod toward the work; at the same time, another motor moves either the welding head or the work lengthwise so that the arc travels, making a bead or a strip of welded material.

The voltage across the arc is the signal that controls the motor that feeds the rod to the work; when the arc voltage rises, the motor must feed the rod faster; a decreasing arc voltage slows or stops the motor, letting the rod burn back to lengthen the arc and bring the arc voltage back to normal.

16-2. Unionmelt Voltage Control (Type UM).—One kind of arc-welding equipment controls its rod motor by the circuit shown in Fig. 16*A*. The motor armature receives its d-c voltage through thyratron tubes 1 and 2, which rectify the a-c voltage supplied by transformer 3*T*. The motor field receives constant current from *S*2*T* and rectifier tube 3. The power supply for making the weld passes through switch *W* (lower left); *W* is left open until the equipment is ready to weld.

When control switch S is closed, transformer $2T$ heats the tubes and soon produces full motor-field current. After the 5-minute timer TD closes its contact, transformer $3T$ applies voltage to the anodes of tubes 1 and 2, and the equipment is ready for welding. Notice that the amount of $3T$ voltage is adjusted or changed by moving the contact on autotransformer SC; this contact is moved by hand, to select the desired motor speed whenever tubes 1 and 2 are firing. When SC is turned clockwise (toward the top, in Fig. 16A), a smaller part of the a-c supply voltage is applied to $3T$, so the motor receives less d-c armature voltage and turns at a lower speed. Usually SC is set so that, if tubes 1 and 2 pass current all the time, the motor moves or feeds the welding rod faster than it is needed. Tubes 1 and 2 act like an "on-off" switch, to apply voltage to the motor for part of each second, so that the motor runs at a lower average speed; this speed is controlled by the grids of tubes 1 and 2.

Tubes 1 and 2 are positive-grid thyratrons,[11-2] a type that fires only when its grid is perhaps 10 volts more positive than its cathode. Tube 1 in Fig. 16A passes current only when there is enough voltage across resistor P so that the P slider is 10 volts more positive than cathode 5. This voltage across P comes from transformer $1T$; whatever a-c voltage the $1T$ secondary (winding 8-to-9) produces, is rectified by tube 4 and is filtered by $1L$, $1C$, $2L$ and $2C$; a larger a-c voltage 8-to-9 causes a larger d-c voltage 2-to-3. (Although P and $4T$ are connected together across this 2-to-3 voltage, most of this voltage appears across P, since the $4P$ winding has much less resistance than P.) The primary of $1T$ is connected (at A and B) across the voltage of the arc that is making the weld.

This arc weld is using a-c welding-power supply (lower left in Fig. 16A), so the arc voltage A-to-B is an a-c voltage.* If this arc voltage increases, the d-c voltage across P increases also.

Before the welding is started, (and with switch W open), the motor may be operated by closing the "Inch" button (lower center in Fig. 16A). This button connects the 6-to-7 voltage (always present across $S2T$) to the secondary of $1T$; the resulting d-c voltage across P makes the tube-1 grid much more positive

* D-c welding-power supply may be used; a switch (not shown) then disconnects transformer $1T$ from the arc voltage, and connects D to D and C to C, so that the d-c arc voltage is applied directly between points 2 and 3.

than cathode 5. Tube 1 passes electrons, which flow from the mid-point of anode transformer $3T$, to 4, through the *RL* switch and the motor armature to point 3, through $4T$ to 5, and cathode to anode of tube 1. Notice that tube 2 is not controlled directly from the *P* slider. Instead, tube 2 fires only after tube 1 fires.* When current flows through tube 1 and $4T$, the secondary voltage of $4T$ charges capacitor $3C$. In the next half cycle, when the tube-2 anode is positive, this $3C$ charge still keeps the tube-2 grid more positive than cathode 3, so tube 2 passes current for its half cycle also. (This arrangement lets tube 2 have a turn-on grid voltage different from tube 1, so these two tubes need not be

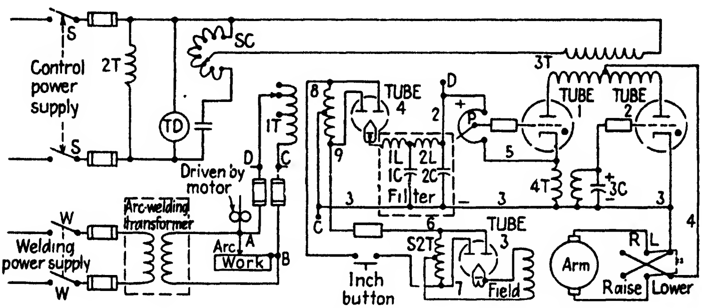


FIG. 16A.—Circuit of Unionmelt arc-voltage control.

closely matched.) As long as the "Inch" button is closed, current flows through tubes 1 and 2 and the armature; the motor turns, lowering the rod toward the work. To raise the rod, the *RL* switch is moved to the other side, reversing the flow of current in the motor armature; when the "Inch" button is closed, the motor turns in the opposite direction.

To start the weld,† switch *W* is closed; at once the arc voltage controls the motor. (The desired arc voltage is set by the position of slider *P*. To get greater arc voltage, the slider is moved toward 5; the 10 volts needed for firing tube 1 now occurs only when total voltage across *P* is larger.) As the motor feeds the rod faster than it can burn back, the arc voltage decreases; the decreased voltage across *P* cannot fire tube 1, so voltage is removed from the motor armature and it begins to stop. At this

* This is like the leading-tube—trailing-tube action described in Sec. 12-16.

† In the Unionmelt process, the rod is first lowered so that it touches a "fuse wad" (like steel wool) placed between the rod and the work. This circuit starts the arc.

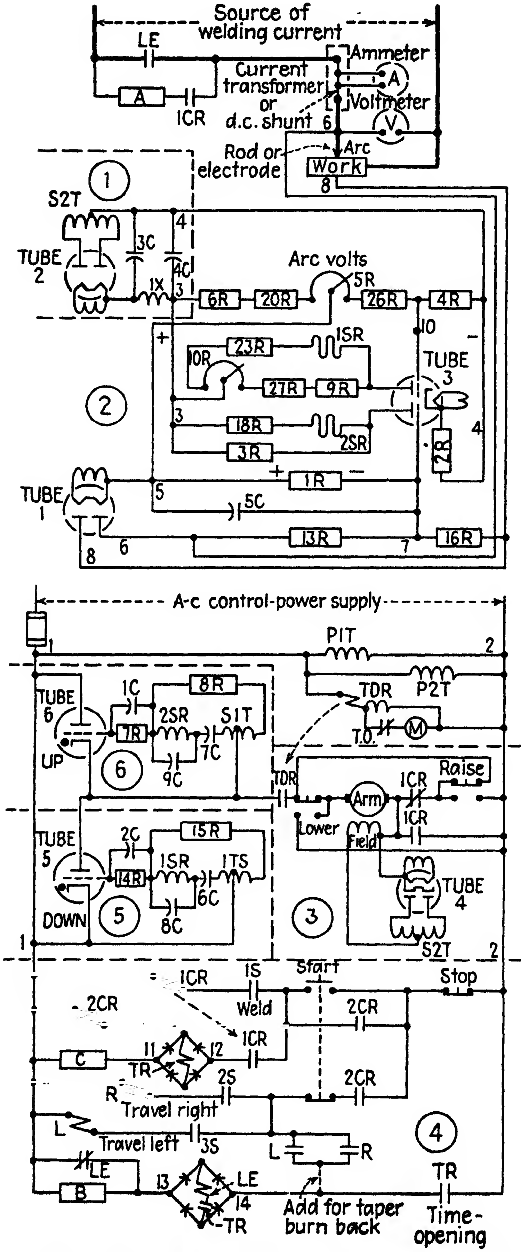


FIG. 16B.—Circuit of arc-welding control (GE type WFB)

lower motor speed, the rod moves more slowly; soon the arc voltage increases, producing enough d-c voltage across P so that tube 1 fires. Tubes 1 and 2 pass current,* increasing the motor speed, again feeding the rod faster than it burns back. This "on-off" action occurs so often that the motor rarely stops or reaches full speed.

16-3. Arc-welding Equipment (GE Type WFB).—The circuit of another automatic arc-welding control is shown in Fig. 16*B*. The rod or electrode motor (in section 3) receives constant field current through tube 4. The motor speed and direction depend on thyratron tubes 5 and 6; any current flowing through tube 5 makes the motor feed the rod electrode down toward the work, while any tube-6 current runs the motor in the other direction, raising the electrode.

Figure 16*B* includes circuits for the welding operation; only those in sections 2, 5 and 6 give electronic control of the arc voltage. When the a-c control power is applied (in the center of Fig. 16*B*), transformers 1*T* and 2*T* warm the tubes and produce the needed d-c supplies from tubes 2 and 4; after 5 minutes, time relay *TDR* operates its contacts. Section 4 shows the circuits of contactors used to control the electrode motor and also the travel motor, which moves the arc along the work. A hand-operated switch may close contacts 1*S*, 2*S* and 3*S* separately. To move the electrode, without welding, 1*S* is kept open; 1*CR* does not pick up, even when the "Start" button is closed. The 1*CR* contacts near the electrode-motor armature are in the right position to let the "Raise" or "Lower" buttons run this motor, as will be described later.[16-7] With 2*S* closed, to "Travel Right," the "Start" button picks up 2*CR*; when the "Start" button is released, the 2*CR* and 2*S* contacts let relay *R* pick up, to operate contacts (not shown) that let the travel motor† move the whole welding head to the right. Similarly, in another switch position the 3*S* contact lets relay *L* pick up, so the travel motor moves the welding head and the arc to the left.

To make a weld, 1*S* is first closed, along with either 2*S* or 3*S*; the "Start" button picks up both 1*CR* and 2*CR*. One 1*CR*

* These thyratrons pass current for the entire cycle or not at all. There is no phase-shifting or gradual control of the current flow in each a-c cycle.

† The travel motor may be an a-c motor or a d-c motor, with its correct power supply.

contact, near the electrode motor, completes the armature circuit so that tubes 5 and 6 can run this motor. Another 1*CR* contact (center of section 4) picks up relay *TR** whose contacts pick up *LE*† (at the bottom of Fig. 16*B*). The main *LE* contact (top of Fig. 16*B*) connects the welding-power supply, so that current may flow between the electrode and the work, at the arc. Notice that connections lead downward from points 6 and 8, so that this arc voltage appears across resistors 13*R* and 16*R*, for automatic control in section 2.

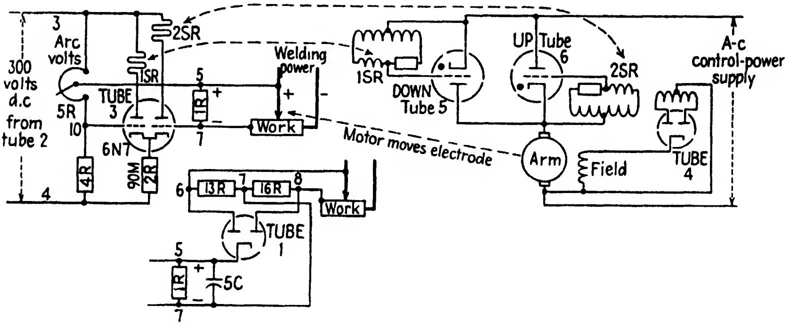


FIG. 16*C*. -Simplified portion of Fig. 16*B*, to show electronic circuits.

In section 1, tube 2 rectifies the voltage of *S2T*; smoothed by the *pi* filter[10-4] (3*C*, 1*X* and 4*C*), a d-c voltage is supplied to section 2; this voltage is positive at point 3, negative at 4. Parts of this d-c voltage are taken from the voltage divider (6*R*, 20*R*, 5*R*, 26*R* and 4*R*) to operate tube-3 grid circuits, explained below.

The operation of the electronic circuits (sections 2, 5 and 6 of Fig. 16*B*) is better shown by Fig. 16*C*; this simpler diagram shows the main circuits of the twin-triode[7-11] tube 3 and the thyratrons 5 and 6. Tubes 5 and 6 are connected back to back[13-8] across the a-c control-power supply; if each tube passes the same amount of

* *TR* is a d-c relay, which picks up instantly when a.c. is applied to points 11 and 12; the disk-rectifier bridge[10-8] changes this a.c. into d.c. suitable for the coil of *TR*. When 1*CR* contact opens, removing the a.c. across 11 and 12, *TR* does not open its contacts instantly (bottom of Fig. 16*B*); about ½ sec passes before the magnetic flux in its core decreases enough to let *TR* drop out.

† *LE* is a large contactor that uses a d-c coil (supplied from a-c points 13 and 14 through a disk-rectifier bridge), which needs less current than a similar a-c coil. After *LE* has picked up, less voltage is needed to hold it closed, so a n-c contact of *LE* opens, inserting resistance *B*.

current, an a-c voltage appears across the motor armature—there is no d-c voltage to make the motor turn either way. To make the motor move the electrode downward, the current through tube 5 must be greater than the tube-6 current.

The thyratron-5 current is gradually increased or decreased by the phase-shifting bridge circuit,[13-7] which includes saturable reactor 1*SR*[28-6]; the tube-6 grid circuit has the same kind of bridge, including 2*SR*. The d-c windings of 1*SR* and 2*SR* receive their direct current through tube 3. Tube 3 controls tube 5, through saturable reactor 1*SR*; when the direct current increases in the left-hand anode of tube 3, the average current also increases in tube 5, as is explained next.

16-4. Phase Shifting by a Saturable Reactor.—Tube 5 of Figs. 16*B* and 16*C* is shown again in Fig. 16*D*, with its phase-shifting bridge made of a constant resistor 8*R* and a variable inductance, which is the saturable reactor 1*SR*.* When no direct current flows in the d-c winding of 1*SR*, this reactor has large inductance or choke effect, which prevents the flow of much alternating current; in a 60-cycle circuit, this reactor now permits the same amount of current to pass through it as would flow through a 30,000-ohm resistor. However, when about 1 or 2 ma of direct current flows through the many turns of the d-c winding, the inductance of 1*SR* has decreased so that it passes as much 60-cycle current as a 1000-ohm resistor.

If less than 1 ma of d.c. flows in 1*SR*, so that it has 5000 ohms, the result is shown at (*b*) in Fig. 16*D*. Since 1*SR* and 8*R* each has 5000 ohms, the vector triangle shows that the tube-5 grid voltage (arrow *G*) lags 90 deg behind the anode voltage (or *S*1*T* voltage),† as shown by *A*; tube 5 fires late, delayed by the amount *A*, and applies voltage to the motor armature for about half of each wave. If both 1*SR* and 2*SR* (in Fig. 16*C*) receive this same amount of direct current from tube 3, then thyratron 6 also fires about 90 deg behind its own anode voltage; tubes 5 and 6 pass

* The grid resistor 7*R* and capacitor 1*C* have a voltage (shown in (*c*) of Fig. 16*D*) to prevent accidental firing of tube 5; see Fig. 13*M* and footnote to Sec. 13-10.

† As arranged in Figs. 16*C* and 16*D*, the *S*1*T* voltage is in phase with the tube-5 anode voltage; the positions of 8*R* and 1*SR* are interchanged from those shown in Fig. 16*B*. In Fig. 16*B*, these *S*1*T* windings are so connected that the *S*1*T* voltage is 180 deg out of phase with the tube anode voltage.

the same amount of current, but in opposite directions, so the d-c motor does not turn.*

We shall see later that, when tube 3 increases the amount of d.c. in 1*SR*, it decreases the d.c. in 2*SR*. As is shown at (*c*) in Fig. 16*D*, increased d.c. in 1*SR* has lowered the ohms of the a-c winding to perhaps 1200. The tube-5 grid voltage lags by only the amount *B*, so tube 5 applies voltage to the motor armature for nearly the entire half cycle, causing a large flow of electrons (downward through the armature in Fig. 16*C*). At the same time, the decreased d.c. in 2*SR* has increased the ohms of its a-c winding to perhaps 20,000 as shown at (*d*). The tube-6 grid

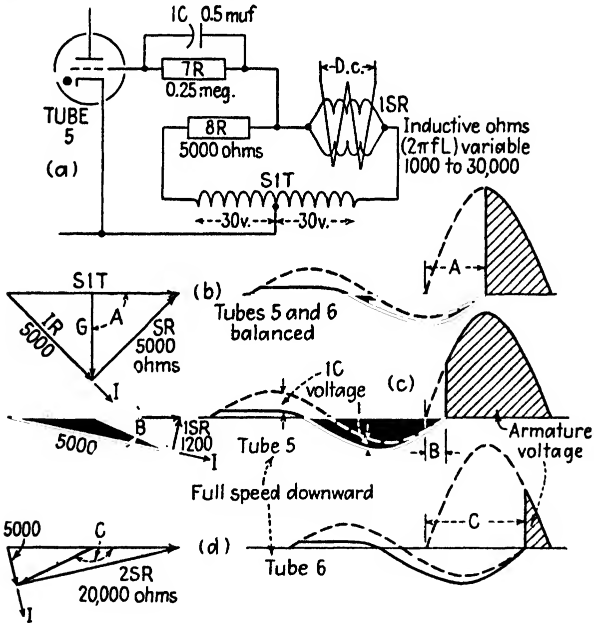


FIG. 16*D*.- Phase-shifting by a saturable reactor.

voltage lags by the large amount *C*, so tube 5 fires very late, and applies voltage to the motor armature for a small part of the half cycle; the electron flow (upward through the armature) is so small compared with the opposite flow caused by tube 5 that the motor

* This arrangement lets unwanted current flow through tubes 5 and 6 in this balanced condition, when the motor is not turning. To decrease the amount of this balanced current, capacitors 6*C*, 7*C*, 8*C* and 9*C* are added near 1*SR* and 2*SR* (in sections 5 and 6 of Fig. 16*B*). These capacitors become resonant[20-8] with various inductance values of the saturable reactors

turns at full speed (moving the electrode downward) almost as if tube 6 were not in use.

If tube 3 gives $1SR$ an amount of d.c. that is only a little greater than the d.c. in $2SR$, then tube 5 passes slightly greater current than does tube 6; the downward flow of electrons (through the armature and tube 5) is enough greater than the upward electron flow (through the armature and tube 6) to make the motor turn slowly, feeding the electrode downward perhaps at the same rate as the electrode burns back.

At any time, if tube 3 gives $1SR$ less d.c. than $2SR$ receives, tube 6 passes greater current than tube 5; the motor turns in the opposite direction, moving the electrode upward, away from the work.

In a phase-shifting bridge such as Fig. 16*D*, we see that an increase of d-c reactor current causes an increase of thyratron current.

16-5. The Comparison Tube—The "Long-tailed Pair."—Tube 3 in Fig. 16*C* includes two triodes whose cathodes are connected together; any current through either triode must pass through cathode resistor $2R$. (This pair of triodes has the "long tail" $2R$.) The incoming signal that controls tube 3 is received at only one grid, point 7; meanwhile the other grid is kept at the steady potential of point 10 on the voltage divider.

If the slider of $5R$ is turned to touch at point 10, and if there is no voltage across $1R$ (as when the electrode is touching the work), grid 7 is at the same potential as grid 10. Each triode has the same grid voltage and passes the same amount of anode current. If the combined anode currents of tube 3 total 1 ma, this current causes 90 volts' drop across cathode resistor $2R$ (90,000 ohms), so that the cathode of tube 3 is 90 volts above point 4. If point 10 (grid potential of tube 3) is 110 volts above point 4, the tube-3 grid voltage is +20 volts. Such a grid voltage permits more than 1 ma total current to flow in tube 3; this greater current causes more voltage drop across $2R$, raising the cathode potential (making the grid voltage more negative) until conditions balance.

To see the "long-tailed pair" work, turn the slider of $5R$ clockwise to a point, say, 20 volts above point 10, to "ask for" 20 volts across the arc. (Also close $1S$ and the "Start" button in Fig. 16*B*.) This new setting of $5R$ raises the grid-7 voltage (since

no arc voltage yet appears between points 5 and 7); the right-hand triode of tube 3 increases the d.c. through $2SR$, to cause greater current through tube 6. This greater current in the right-hand part of tube 3 also causes greater voltage drop across $2R$; the cathode potential of tube 3 rises, while its left-hand grid stays at the same potential 10. The current decreases in the left-hand triode of tube 3, decreasing the d.c. in $1SR$. Notice that raising the grid-7 potential increases the current in the right-hand triode, but decreases the current in the left-hand triode; the total current through tube 3 increases a very small amount. While the tube-6 current increases, the decreased d.c. in $1SR$ causes less tube-5 current; the motor turns at full speed, to raise the electrode from the work so as to increase the arc voltage.

As the arc voltage nears the 20 volts selected by $5R$, the voltage across $1R$ increases; this $1R$ voltage is more negative at the grid-7 end, so it lowers the grid voltage of the right-hand triode. As this gradually reduces the d.c. in $2SR$, the voltage drop across $2R$ decreases; the current in the left-hand triode increases until the $1SR$ current equals the $2SR$ current and the motor stops. As the electrode now burns back and increases the arc voltage further, the voltage across $1R$ increases and makes grid 7 more negative; the $2SR$ current and tube-6 current decrease, the $1SR$ current and tube-5 current increase until the motor moves the electrode downward just as fast as the electrode burns back.* The voltage across $1R$ is being compared with the voltage between point 10 and the $5R$ slider. (This 10-to-$5R$-slider voltage is the reference voltage, mentioned in Sec. 15-6.) Tube 3 acts as a comparison tube, for its action "compares" the grid-7 voltage with the grid-10 voltage; it makes the motor correct conditions until these grid voltages become equal.

16-6. Welding with A.C. or D.C. of Either Polarity.—The main diagram of Fig. 16C requires that the electrode always be more positive than the work; this is not possible when a-c welding power is used. A separate diagram (lower center in Fig. 16C) shows how tube 1 is added so that this welding equipment may use various arrangements of welding-power supply.

Connected between the electrode and the work, resistors $13R$ and $16R$ divide the arc voltage into two equal parts. Whenever

* The slider on resistor $10R$ (in section 2 of Fig. 16B) is adjusted to give this steady downward movement of the electrode.

electrode (6) is more positive than work (8), electrons flow from 8 through 16*R* to 7, up through 1*R* to 5, and through the left-hand anode of tube 1 to point 6. A half cycle later, or whenever electrode (6) is more negative than work (8), electrons flow from 6 through 13*R* to 7, up through 1*R* and the right-hand tube-1 anode to point 8. In each case, this flow is upward through 1*R*, and makes grid 7 more negative than point 5. With a-c welding power, the rectified voltage across 1*R* is pulsating; a capacitor such as 5*C* removes much of this ripple.

Using tube 1 in this way, the voltage across 1*R* is always negative at the grid-7 end for any kind of welding-power supply.

16-7. Controlling the Arc-welding Equipment.—When the "Start" button closes, in Fig. 16*B*, there is no arc and the electrode is often far from the work. This open circuit applies more voltage between points 6 and 8 than is needed; the large voltage across 1*R* decreases the d.c. in 2*SR*, increases the d.c. in 1*SR* so that tube 5 makes the motor feed the electrode toward the work. When the electrode touches the work and causes the arc, the 6-to-8 voltage drops to a very low amount; tube 6 now reverses the motor, so that it moves the electrode away from the work until the desired voltage appears across the arc.

Although the "Stop" button (in section 4 of Fig. 16*B*) drops out 1*CR* and 2*CR* instantly, the time delay (before *TR* opens)* also keeps *LE* energized for an extra half second; during this delay, welding current continues to flow. The electrode motor is stopped, so the electrode is still; it burns back during the time delay and fills the arc crater with metal. If the *L* and *R* contacts are connected by a wire (added at the bottom of Fig. 16*B*), the welding head continues to travel during this delay, causing a sloping or tapered end to the weld. This gives "taper burn back."

While 1*CR* is not energized, the motor may be run by the "Raise" or the "Lower" push button. Since *LE* is not closed, there is no arc voltage; the voltage across 1*R* is zero, so grid 7 is at the positive potential of point 5. Enough d.c. flows through 2*SR* to turn on tube 6. (With no arc voltage, tube 5 never passes current.) When the "Raise" button is pushed (in section 3 of Fig. 16*B*), electrons flow from right-hand point 2 through the button and 1*CR* n-o contact, through the armature, *TDR* con-

*See Sec. 16-3, footnote.

tact, cathode to anode of tube 6, to point 1. To make the motor lower the electrode, the "Lower" button reverses the armature voltage; electrons flow from 2 through the "Lower" contacts, to the right through the armature, through 1*CR* and the "Raise" button upper contact, through *TDR* and tube 6. No matter which button is pushed, tube 6 fires.

Questions

True or false? Explain why.

1. In Fig. 16*A*, closing the "Inch" button increases the voltage across the motor field.

2. If capacitor 3*C* in Fig. 16*A* becomes shorted, tube 2 fires whenever its anode is positive.

3. In Fig. 16*C*, two thyratrons may be used in place of tube 3, so that one thyratron turns off when the other thyratron turns on suddenly.

4. Using tube 1 in Fig. 16*C*, the voltage across 1*R* is less than half of the arc voltage.

5. If the heater of tube 1 (Fig. 16*C*) burns open, the motor moves the electrode downward.

6. In Fig. 16*C*, if the voltage across 4*R* is 110 volts, and if 2*R* is decreased to 30,000 ohms, will the total tube-3 current be about (*a*) 0.1 ma? (*b*) 1.2 ma? (*c*) 3.5 ma? or (*d*) 10 ma?

7. Which type of thyratron fires if its grid circuit is open? (*a*) negative-grid type? (*b*) positive-grid type?

8. In Fig. 16*D*, if there is no d.c. in 1*SR*, is the voltage across 8*R* about (*a*) 50 volts? (*b*) 10 volts? or (*c*) zero?

9. If *R*8 (of Fig. 16*D*) burns open, is thyratron 5 made to fire (*a*) early? (*b*) about midway in the half cycle? or (*c*) late?

CHAPTER 17

VOLTAGE AND SPEED REGULATORS

In the preceding chapters various tube circuits are used to control the speed of a motor. When a slider or a speed-control dial is moved to select a desired motor speed (in Figs. 15*J*, 15*K* or 15*M*), the tube-operated circuit controls the motor voltage so that it runs at this speed. Similarly, when dials are set to select a desired arc voltage (in Figs. 16*A*, 16*B* or 16*C*), tubes control the motor speed so that this arc voltage is obtained. Each of these circuits is an electronic voltage regulator. Let us see how such circuits work like a simple voltage regulator used with a generator.

17-1. The D-c or A-c Generator.—A d-c generator looks like the motor described in Sec. 14-1 However, instead of using electric power and driving a load, the generator produces electric power; it must be driven by some engine or motor. If the generator stops turning, it produces no electricity. When the generator is being driven at the required speed, it produces no voltage or electric power unless direct current flows in its field winding.* When there is field current, the driving engine must deliver more power, as the generator produces voltage; when this voltage forces current through a load, much greater power is required from the engine. The produced voltage increases when the generator is driven faster; the voltage also increases when the field current is increased.

An a-c generator acts in the same way; direct current must flow in its field winding, and the amount of this field current controls the amount of a-c voltage produced

Even if it is driven at constant speed and with steady field current, the produced voltage or output voltage changes when greater load current is taken from the a-c or d-c generator. To bring the voltage back to the desired amount, the field current must be increased each time the load current increases. To

* This is not true for a tachometer generator,[28 1] which has permanent magnets to give its field strength.

control the field current in this way, a generator-voltage regulator is used.

17-2. The Voltage Regulator.—In Fig. 17*A*, a simple regulator is shown controlling the voltage *GV* produced by generator *G*. This regulator is a relay whose coil *V* is operated by the voltage *GV*. Direct current flows through the regulator contact and the generator-field winding; this contact *C* is held closed by the spring *S*. When the generator produces more than 115 volts, this voltage forces enough current to flow through the regulator coil *V* so that its downward pull (on its metal core) is greater than the upward pull of the spring *S*; the metal core moves downward, opening contact *C*. The resistance *R* is now in circuit

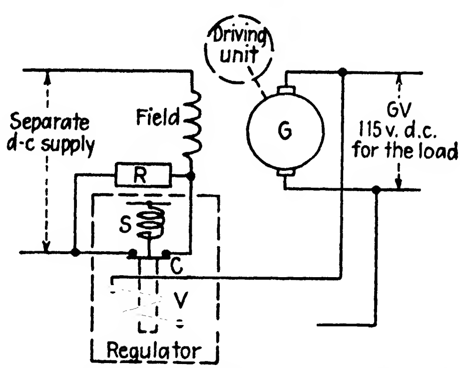


FIG. 17*A*.—Simple voltage regulator with spring.

and decreases the amount of field current; this decreases the voltage G*V* to perhaps 113 volts. At this lower voltage, less current is forced through the regulator coil *V*; as its downward pull is not so great as the upward pull of spring *S*, contact *C* closes. This short-circuits *R* and increases the field current and the voltage *GV*. The contact *C* opens and closes often, to keep the *GV* voltage close to the desired 115 volts. If the load current suddenly increases, causing the *GV* voltage to drop, contact *C* stays closed until the amount of field current increases to the greater amount needed; the *GV* voltage returns to normal before contact *C* opens again.

Notice that the strength of the spring *S* is the standard or guide which sets the amount of *GV* voltage produced by *G*; to raise this *GV* voltage to, say, 120 volts, spring *S* must be tightened (or a stronger spring must be used) so that contact *C* does

not open until a greater current flows in coil V, forced by 120 volts. In any regulator, there must be such a standard or reference; if the produced voltage is greater than this standard, the regulator reduces the voltage. The regulator tries to hold whatever voltage the standard "tells" it to hold.

While moving-contact regulators are used with most generators, tube-operated circuits may regulate the voltage and speed with greater accuracy. Let us see how a tube may be used in this way.

17-3. Tube Response to Generator Voltage.—To keep a simple circuit, Fig. 17B includes a generator G, which is so small that

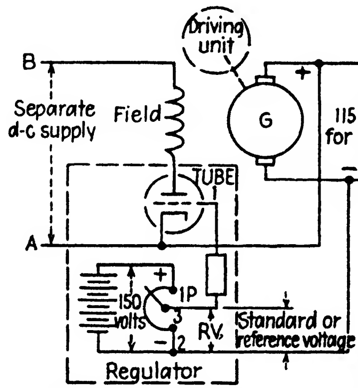


FIG. 17B.—Voltage regulator with tube and reference battery.

its d-c field current can pass directly through a high-vacuum tube 1. (Later[17-5] other circuits will be added to permit use with larger generators.) When the grid of tube 1 permits, electrons flow from terminal A, cathode to anode of tube 1, through the generator-field winding to terminal B. Such a tube circuit has no spring like the regulator of Fig. 17A; to provide a similar standard or guide, Fig. 17B includes a 150-volt battery. The slider of 1P (connected across this battery) is turned to select the amount of voltage that the generator G should produce.

If 1P is set (extreme clockwise) so that 150 volts appears between slider 3 and point 2, this makes the tube-1 grid 150 volts more positive than terminal 2 of generator G. If G is producing, say, 100 volts, its terminal 1 (connected to the cathode of tube 1) is 100 volts above (or more positive than) point 2, but is still 50 volts below (more negative than) point 3. Since the grid 3 of

tube 1 is 50 volts more positive than cathode 1, tube 1 is passing full current, to increase the generator voltage. When this *GV* voltage reaches about 155 volts, cathode 1 is 155 volts above 2, while grid 3 is 150 volts above 2, so tube 1 has a grid voltage of -5 (which is about right to let tube 1 pass the field current needed to make *G* produce 155 volts).

By turning *1P* so that *RV* (the reference voltage 3-to-2) is about 122 volts, the tube-1 current decreases until *GV* is only 115 volts. (Now the tube-1 grid voltage is about -7 volts.) At

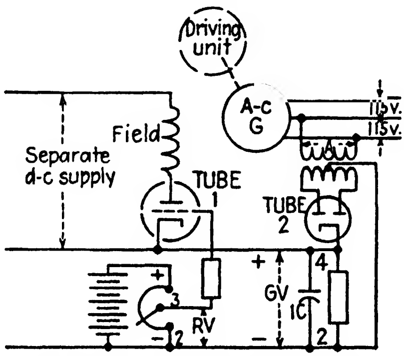


FIG. 17C.—Regulator of Fig. 17*B*, controlling a-c generator.

this setting of *1P*, tube 1 regulates the generator voltage *GV* at 115 volts. If a sudden increase of generator load causes *GV* to drop a bit below 115 volts, this lowers the cathode potential of tube 1; the increased tube-1 anode current strengthens the generator field, so that *GV* returns to 115 volts.

Although a battery is used in Fig. 17*B*, this reference voltage may be obtained, instead, from a separate rectified d-c supply, usually including a voltage-regulator tube.[10-6]

Just as Fig. 17*B* shows how tube 1 may regulate the voltage of a d-c generator, Fig. 17*C* shows that the same tube may regulate the voltage of an a-c generator. The only difference is, with the a-c generator, that its a-c voltage *A* is first rectified by tube 2 and smoothed by capacitor *1C*. The resulting d-c voltage *GV* (4-to-2) is "compared"* with *RV* (3-to-2); tube 1 then corrects

* Tube 1 compares these two voltages; voltage *GV* is the height of tube-1 grid potential above point 2—voltage *RV* is the height of tube-1 cathode potential above point 2. If either of these two voltages changes, it changes the grid voltage (grid to cathode) of tube 1 so that the tube-1 anode current

the field current to make generator *G* produce the desired a-c voltage.

17-4. A Speed Regulator.—A similar tube circuit will regulate the speed of a d-c motor, such as *M* in Fig. 17*D*. Here tube 1 controls the field of generator *G*; a greater field current raises the voltage *D* (produced by *G*) and therefore increases the speed of motor *M*. Although this voltage *D* is sometimes used as a signal to show the motor speed, a more accurate speed signal is produced by a tachometer[28-1] generator *T*, driven by motor *M*.

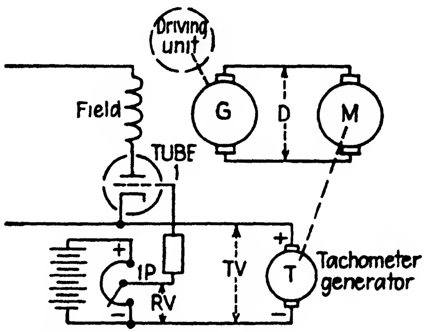


FIG. 17*D*.—Voltage regulator for speed control of motor *M*

In Fig. 17*D*, the tachometer voltage *TV* increases at the same rate as the speed of *M* increases.

This tube-controlled circuit is still a voltage regulator; if the tachometer voltage *TV* becomes too small, as compared with the reference voltage *RV*, tube 1 controls generator *G* until the *TV* voltage rises to the correct amount. Since this *TV* voltage cannot rise unless the speed of motor *M* also rises, the circuit of Fig. 17*D* also controls motor speed, merely as a "by-product" of holding the correct voltage at *TV*. If the 1*P* slider is turned (counterclockwise) to select a smaller reference voltage *RV*, the speed of *M* decreases until *TV* is again the correct amount; in this way 1*P* becomes a speed-adjusting dial.

17-5. A High-vacuum Tube May Control Large Field Current. Still using the voltage-regulating circuits shown in Figs. 17*B*, 17*C* and 17*D*, the high-vacuum tube 1 may control much larger

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also changes, to regulate the generator voltage.

Notice that *GV* is not exactly the same number of volts as *RV*, the slight difference between *GV* and *RV* becomes the grid voltage of tube 1 and must change slightly to cause the tube-1 current to change.

generator-field current if we add an "amplifier" between tube 1 and the large field winding. Two kinds of amplifier often used in such regulators are shown within the dashed rectangles in Figs. 17*E* and 17*F*; either of these rectangles may be controlled by tube 1. In Fig. 17*E*, the amplifier consists of two thyratrons,

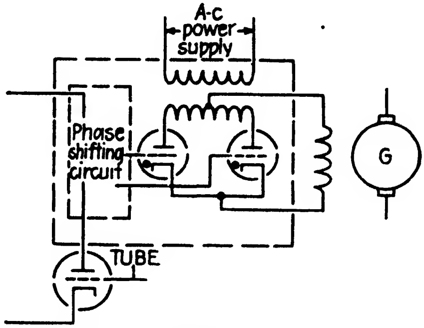

FIG. 17*E*.—Small tube 1 controls large generator, by phase-shifted thyratrons.

which rectify and control the large field current; these thyratrons are phase-shifted by any one of several methods[13-15] already explained; in this way the small increase in tube-1 anode current causes a large increase in the generator-field current.

In Fig. 17*F*, the amplifier is not electronic, but consists of a special d-c machine, such as an amplidyne,[28-2] which is driven

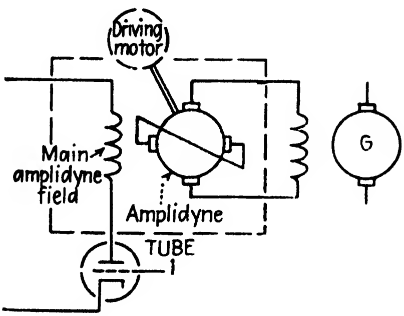

FIG. 17*F*.—Small tube 1 controls large generator, by an amplidyne amplifier.

at constant speed by a separate motor. The main-control-field current of this amplidyne passes directly through tube 1; an increase of 10 ma in tube 1 may cause more than 20 amperes increase in the direct current that the amplidyne supplies to the field of generator *G*.

Coming, next, to various tube-operated voltage regulators often used in industry, we shall find that their circuits operate on the basic ideas of Figs. 17*B*, 17*C* or 17*D*, and that they include phase-shifted thyratrons or a rotating amplifier (such as the amplidyne); the reference voltage *RV* (supplied before by a battery) may come instead from a rectifier, a filter and a voltage-regulator tube.

17-6. Voltage Regulator (Weltronic Model VR1).—This regulator circuit in Fig. 17*G* is described first, because many of its parts have been explained in Secs. 15-8 to 15-12. The a-c generator is shown near the center of Fig. 17*G*. The generator field receives its direct current from thyratron tube 5 and phanotron tube 6. As has been explained before,[15-12] only one tube of this pair needs to be grid-controlled when supplying current to an inductive load, such as the field winding.

The phase-shifting circuit that controls tube 5 is the same as that shown in Fig. 15*M*. At the right-hand side of Fig. 17*G*, if the tube-7 grid is made more negative, less current flows through tube 7 and resistor 8*R*; point 17 rises, increasing the tube-8 current, which flows also through the d-c winding of saturable reactor 6*T*. This increased d.c. decreases the inductance of the a-c winding of 6*T*. This shifts the phase of the a-c grid voltage of tube 5 (see Sec. 16-4 and Fig. 16*D*) so that more current flows through tubes 5 and 6. Briefly, the field current and generator voltage increase when the tube-7 grid is made more negative.

In the upper part of Fig. 17*G*, transformers 2*T*, 4*T*, 5*T* and 7*T* operate from the a-c control-power supply, at constant voltage. However, transformer 1*T* is connected across one phase (between two of the three leads) of the a-c generator; the secondary voltage of 1*T* is rectified by tube 2, smoothed by 4*C*, and produces a d-c voltage across resistance 1*P*. The slider of 1*P* is moved, to select the desired output voltage that the a-c generator furnishes at *A*; the d-c voltage *GV* (between 1*P* slider 10 and point 8) is used in the tube-7 grid circuit. When the generator voltage *A* increases, the voltage *GV* also increases (like the circuit of Fig. 17*C*).

At the left-hand side of Fig. 17*G*, tube 1 rectifies the 4*T* voltage; smoothed by 2*C*, the d-c voltage is applied across the 150-volt regulator tubes 3 and 4; a steady voltage[10-6] appears between points 9 and 10, while any voltage change is taken by 2*R*. This steady 300 volts is the reference voltage *RV*.[17-2]

See how tube 7 "compares" *RV* against *GV*. Cathode 9 of tube 7 is always 300 volts more positive than point 10. If there is no a-c generator voltage and no voltage at *GV*, then point 8 (grid potential of tube 7) is at the same potential as point 10, which makes the grid 300 volts more negative than cathode 9; tube 7 passes no current, so tubes 5 and 6 are passing the greatest amount of field current. If the generator is running, this field current now increases the generator voltage *A*; voltage *GV*

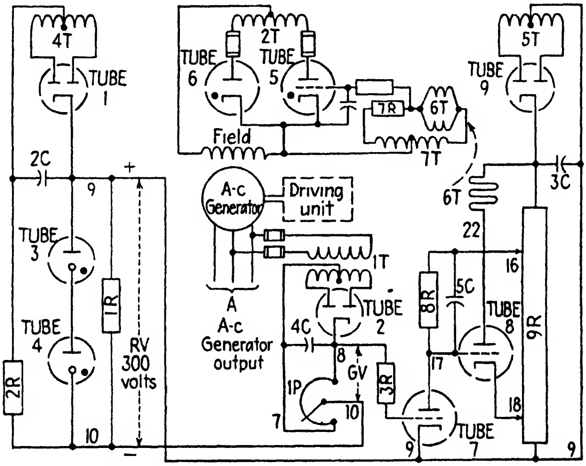

FIG. 17G.—Circuit of Weltronic voltage regulator (model VR1).

increases, raising the potential of point 8 (tube-7 grid). When *GV* becomes about 285 volts, grid 8 is now only 15 volts more negative than cathode 9, and tube 7 may pass a very little current.* At, say, 292 volts, the -8 grid voltage lets tube 7 pass enough current to decrease the field current slightly, so that the generator produces just enough voltage *A* to hold 292 volts at *GV*. Conditions are balanced.

If the slider of *1P* is turned (clockwise) toward point 8, a smaller part of the total generator voltage now appears at *GV*. Voltage *GV* becomes less for a short time, but this lowers the potential of grid 8 so that tube 7 immediately "calls for" greater field current; the generator voltage *A* increases until the total

* The exact grid voltage that permits current to begin to flow (called *cutoff*[3-11]) depends, of course, on the characteristics of whatever tube is used. Although it is of great importance to the circuit designer, this detail does not concern us here.

voltage 8-to-7 across 1P is greater than before. The part GV returns nearly to its previous amount. In this way, *1P* sets the generator voltage.

If increased a-c load on the generator reduces the voltage *A*, this lowers *GV*, making tube 7 "call for" more field current to bring the voltage *A* back to normal. What is normal? It is the amount of voltage *A* that makes *GV* match correctly with the standard or reference voltage *RV*. The success of the regulator circuit depends on *RV*'s remaining steady and constant.

17-7. Voltage Regulator (General Electric Type GVA1B1).—The voltage of an a-c generator is controlled also in Fig. 17*H*. The generator field receives its direct current from thyratron tubes 1 and 2; each thyratron is phase-shifted an equal amount by the a-c grid voltage from transformer *S2T*. This a-c voltage lags the thyratron anode voltage by about 90 degrees. (If 10*R* is adjusted so that only 2660 ohms remain in circuit, this resistance matches[13-5] the 1-mu f capacitor 10*C* so that the *S2T* voltage lags exactly 90 degrees.[13-5] Notice resistors 8*R* and 9*R*, used instead of a transformer center tap between 11 and 12.)

This fixed *S2T* voltage is raised or lowered by a d-c voltage (as explained in Sec. 15-5); this d-c voltage appears between point 6 (cathode of tubes 1 and 2) and point 5. The potential at point 6 changes little, while point 5 rises when tube 6 passes less current. When point 5 rises, tubes 1 and 2 are fired earlier in each half cycle. Briefly, when tube 6 passes less current, this increases the field current and the generator voltage.

All circuits in the lower portion of Fig. 17*H* receive their power from the voltage produced by the a-c generator; (this includes also the filament supplies of tubes 3, 4, 5 and 6). The a-c voltage produced between lines 1 and 2 is rectified by tube 3 and appears between *W* and *X*. Similarly, the a-c voltage between 1 and 3 is rectified by tube 4, producing d.c. between *X* and *Y*. Tube 5 rectifies the 2-3 a-c voltage. The three d-c voltages *WX*, *XY* and *YZ* are connected in series so that the total voltage *WZ* includes a voltage signal from each of the three a-c phases. This *WZ* voltage is smoothed[10-4] by the filter (1*C*, 1*R* and 2*C*). The resulting d-c voltage is connected across a voltage divider (2*R*, 3*R*, 4*R*, voltage-regulator tube 7 and 8*R*). If 8*R* is turned (clockwise) to short all its resistance, all of the a-c generator voltage is used for producing the d-c voltage between 4 (top) and 7 (bottom);

the lowest amount of generator voltage results. To increase the generator voltage, $8R$ is turned (counterclockwise) to insert resistance; voltage WZ now becomes larger, to make up for the voltage across $8R$.

When control power is first connected to anode transformer $1T$, the thyratrons are warmed for 5 minutes before the field

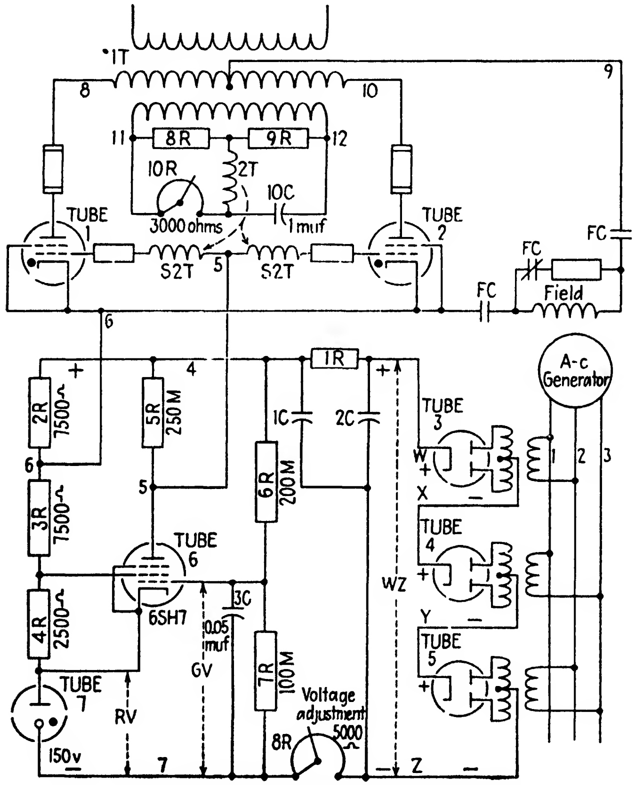

FIG. 17*H*.—Circuit of a-c voltage regulator (GE type GVA1B1).

contactor closes its contacts *FC*. Not until then does the generator produce voltage, so tubes 3 to 6 are not yet warmed. For a moment there is no voltage at *WZ* or across resistors $2R$ or $5R$; there is no voltage difference between points 5 and 6, so tubes 1 and 2 give reduced field current (depending on the setting of $10R$).

As tubes 3, 4 and 5 begin to pass current, about 600 volts appears at *WZ*. Less than one-third of this voltage appears across resistor $7R$, and becomes the signal voltage *GV*, between

point 7 and the control grid of tube 6. If the a-c generator voltage increases, WZ increases and so does GV; meanwhile, the reference voltage RV remains unchanged, between point 7 and the tube-6 cathode, thanks to the 150-volt regulator tube 7. When a rise in generator voltage increases GV, more electrons flow from Z, through $8R$, tube 7, cathode to anode of tube 6, through $5R$ and $1R$ to W. The voltage drop increases across resistor $5R$, so the potential of point 5 is lowered, phasing back tubes 1 and 2 so that they fire later; the field current decreases, bringing the generator voltage down to normal.

17-8. Voltage Regulator with Amplidyne (Type GVA7B1).—To control the voltage produced by the a-c generator in Fig 17I, the generator-field current is varied by using an amplidyne (see Secs. 17-5, 28-2 and Fig. 17F). In turn, the direct current produced by the amplidyne depends on the tiny currents flowing in its several field windings, shown below the amplidyne armature circle. The amplidyne is being driven by some motor not shown.

At the right-hand side of Fig. 17I, voltage from one phase of the a-c generator is used as a signal, and also the control-power supply for all tubes. Before the generator produces its voltage, the tube circuits are connected (through contacts B) to an a-c lighting circuit, so that the amplidyne produces enough generator-field current for about 115 volts' output. When the generator goes into service, a relay opens contacts B and closes contacts A. This a-c voltage from the generator is rectified by tubes 3 and 5; smoothed by $1L$ and $1C$, a d-c supply for the amplidyne fields appears between points 8 and 6, while a separate d-c supply for tube 1 appears between 4 and 7. We shall see that the a-c generator-voltage signal controls tube 1, which in turn makes tube 2 vary the main amplidyne field to regulate the generator voltage.

Tube 1 receives two voltage signals and "compares" them. At tube-1 cathode, the reference voltage RV keeps this cathode always 105 volts more positive than point 7. The tube-1 control grid receives the voltage GV, which increases when the d-c voltage across $2R$ (at the left) increases; the slider of $3R$ is turned to select the desired a-c generator voltage. (Meanwhile, the screen grid of pentode tube 1 is connected through $5R$ to a positive potential on $1R$, and does not affect the tube-1 current. For now, do not include the dotted portions such as $3C$, $5C$, $6R$ or the circuit above the amplidyne armature; these are added into

the circuit later.[17-11]) Because of transformer $2T$, the voltage across $2R$ may be about 300 volts when the a-c generator produces its full 120 volts' output. Under this condition, the $3R$ slider is in such a position that only about 100 to 105 volts appears at GV; the tube-1 grid voltage is slightly negative, and there is a small electron flow from point 7, through tube 4, cathode to anode of tube 1, through $4R$ to point 4. This flow causes enough voltage drop across $4R$ so that the potential at point 6 is perhaps 25

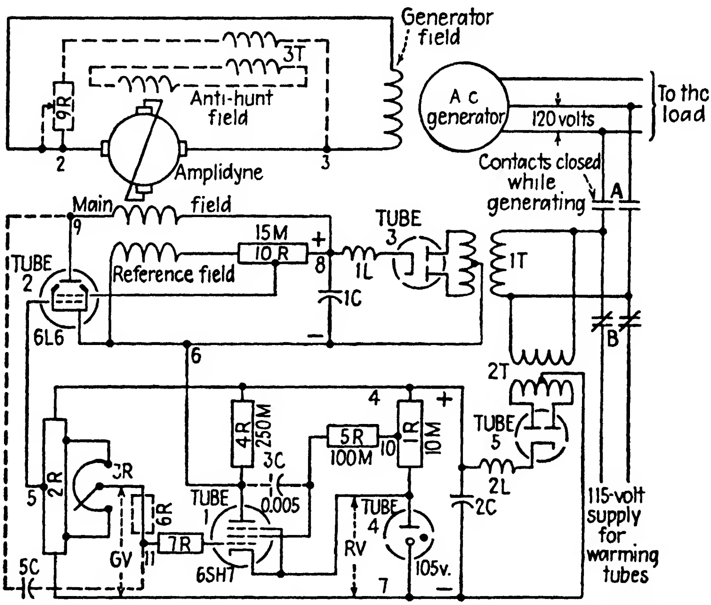

FIG. 17*I*.—Voltage regulator with amplidyne (GE type GVA7B1).

volts above the potential at point 5 (which is the midtap on $2R$, and connected to the tube-2 grid). With this -25 grid voltage, the beam power tube 2 permits only a small electron flow from cathode to anode and through the main amplidyne field to point 8.

The two field windings (shown below the amplidyne in Fig. 17*I*) oppose, or buck, each other. The reference field receives direct current steadily (though $10R$) and alone causes enough field strength to make the amplidyne produce its largest amount of direct current, which in turn makes the a-c generator produce its greatest a-c voltage. Any current passing through tube 2

and the main field produces a field strength, which reduces the total field strength of the amplidyne. Therefore, greater tube-2 current causes less a-c voltage output from the generator. For the generator to produce 120 volts a.c., the tube-2 current must be quite small.

To see the regulating action in Fig. 17*I*, suppose that the a-c generator voltage rises slightly; this increases *GV* a fraction of a volt (while *RV* stays unchanged), so the tube-1 grid voltage becomes less negative. The tube-1 anode current increases slightly, causing several volts' greater drop across 4*R*; this lowers the cathode-6 potential of tube 2 (while its grid 5 has much less change). The tube-2 anode current increases, strengthening the main field; this reduces the total field strength of the amplidyne so that the field of the a-c generator is also weakened and the a-c generator voltage is reduced to normal.

17-9. Voltage Regulator (CR7507-C116A).—This circuit in Fig. 17*J* is like that of Fig. 17*H* in the use of thyratron tubes 1 and 2, which are phase-shifted by the a-c quadrature (lagging-90-deg) wave from *S2T*, raised or lowered by the d-c voltage[15-5] appearing between points 5 and 6. A single phase of the a-c generator voltage is rectified by tube *E* and filtered, to give a d-c signal voltage between points 9 and 7, which increases as the generator voltage increases. (The dotted parts, such as tube *G*, adjusters 3*P* to 6*P*, 10*R*, 11*R*, 12*C* and 13*C* will be discussed later.[17-13] For now, do not include these parts.)

Some parts of this complete voltage regulator are not shown in Fig. 17*J*. Before contactor *M* can close its contacts (upper right-hand corner), all tubes are warmed for about 5 minutes; other transformers provide the heater voltages and the anode voltage for tube *A*. Then a push button may pick up contactor *M*, connecting anode voltage to tubes 1 and 2, to furnish field current to the generator.

The d-c voltage between points 4 (top) and 8 (bottom of Fig. 17*J*) is obtained through rectifier tube *A*, and is divided into three equal parts by the voltage-regulator tubes *B*, *C* and *D*. Tube *D* supplies the reference voltage *RV*, so that the cathode of pentode tube *F* is always 105 volts more positive than point 8. The tube-*F* control grid is connected through 9*R* to point 10, which is at a potential halfway between the 2*P* slider and the 1*P* slider; the voltage from mid-point 10 to point 8 is *GV*, the genera-

tor-voltage signal, which is compared to *RV* so as to control tube *F*.

After the 1*P* slider is set (to select the desired generator voltage), the potential at 1*P* slider remains fixed or steady. However, the potential at the 2*P* slider becomes more positive as the generator voltage increases. If there is no generator voltage (as when contacts *M* are open), there is no voltage drop across 4*R*, 2*P* or 5*R*, so the 2*P* slider is at the same potential as point 7. At this time, if 1*P* slider is turned to the end near 6*R*, where it is about 60 volts below (more negative than) point 7, we see that

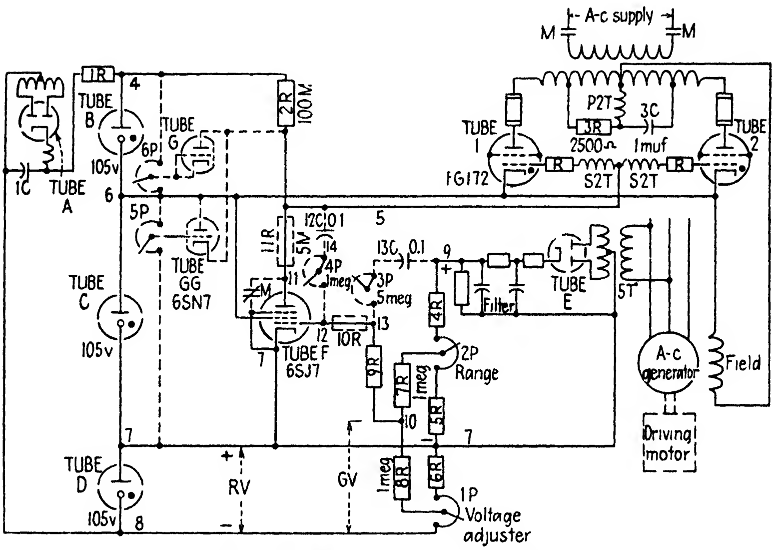

FIG. 17*J*. Voltage regulator (CR7507-C116A).

point 10 is now 30 volts below point 7. Since points 10 and 7 are connected also to the control grid and cathode of tube *F*, this −30 grid voltage prevents the flow of anode current through tube *F* or resistor 2*R* (at top). Since there is now no voltage drop across 2*R*, point 5 is near the potential of point 4, which is 105 volts above point 6 (cathode of tubes 1 and 2). The thyratron grids (at point 5) are much more positive than cathode 6, so tubes 1 and 2 are ready to pass full anode current as soon as contactor *M* applies anode voltage. (However, another *M* contact prevents this sudden "turn-on" action, as is described later.[17-13])

When the generator produces voltage, part of this voltage

(rectified by tube *E*) appears across 2*P* and 5*R* so that the potential at the 2*P* slider rises. The potential at point 10 also rises (half as much), so that the tube-*F* control grid becomes less negative; quickly this grid lets electrons flow from cathode 7 to the anode of tube *F* and through 2*R* to point 4. This flow through 2*R* lowers the potential at point 5; when point 5 nears the same potential as cathode 6, the grid-voltage waves of *S2T* delay the firing of tubes 1 and 2 later in each half cycle. This prevents the field current from increasing so fast.* Finally the generator voltage becomes the right amount so that the voltage from 7 to 2*P* slider is nearly equal to the voltage from 7 to 1*P* slider. Point 10 has nearly the same potential as point 7; voltage *GV* is nearly equal to *RV*. Tube *F* now passes that amount of current needed to hold the point-5 potential at the right value so that tubes 1 and 2 provide just enough field current to cause this generated voltage to appear. We see that an endless chain of responses causes a balance in this closed-cycle type of control.

If 1*P* slider is turned clockwise, this lowers for an instant the potential of point 10 and the tube-*F* control grid. Less tube-*F* anode current raises the point-5 potential, firing tubes 1 and 2 earlier so that the field current and generator voltage increase. This greater generator voltage increases the voltage between 7 and 2*P* slider, raising point 10 back to a regulated position. Clockwise movement of 1*P* increases generator voltage. When the 2*P* slider is moved clockwise, the generator voltage must increase still further to reach a regulated condition; 2*P* sets the voltage range through which 1*P* may adjust the generator voltage.

17-10. Hunting Action in a Regulator Circuit.—While the circuits in this chapter have been explained without mentioning "hunting," all such circuits need extra parts whose only purpose is to prevent hunting; these added parts are *antihunt devices*. Without them, the generator voltage may swing from a low amount to a high amount, then back to low voltage again, repeating this action over and over, without being able to steady itself at the desired voltage. The voltage is hunting for a steady amount or setting, but seems unable to find or reach it without "over-shooting" in each direction.

* Described step by step, the action of this circuit may seem slow. However, the entire action occurs very quickly.

Similarly, when a new driver is learning to steer an automobile, he sees that the car is going too far to the right, so he swings the wheel to the left. Now the car goes too far to the left, so he swings the wheel back to the right. The car is hunting for the center of the road; the movements of the steering wheel are so large and so fast that the car crosses the road center but cannot stay in the center. Here an "antihunt" action is used when this driver learns to move the wheel smoothly—when he straightens the wheel quickly after each small turn away from center. A good driver turns his wheel very little when the car is moving slowly toward the road edge; usually this small correction is all that is needed. However, if the car is leaving the road faster, he turns the wheel more sharply, then straightens it again. Notice that he turns the wheel, not so much because of a small error in direction, but because that error is increasing. The greater the change in direction, the more correction is needed.

Most electronic circuits act so fast that they can overcorrect for a signal error before other parts of the equipment can cause normal correction. This overcorrection causes hunting. Often the cure is merely to add a small time-delay action to slow the circuit response.

Near the bottom of Fig. 17*H*, notice that capacitor 3*C* is added across 7*R* to delay any change of the tube-6 grid voltage. The amount of delay is a small part of a cycle.* A larger capacitor or resistor delays the circuit response more than is needed.

17-11. Antihunt Action in Amplidyne Regulator.—Using only those parts of Fig. 17*I* already explained,[17-8] let us watch this circuit hunt. When the generator voltage increases (and *GV* increases), tube 1 increases the voltage drop across 4*R*, so the tube-2 current also increases; the total amplidyne field strength becomes much lower, so the a-c generator voltage now swings to a lower value. This downward swing lowers *GV* so fast that tube 1 turns off tube 2; the total amplidyne field strength increases a large amount, so the a-c generator voltage again rises higher than is desired. This up-and-down action (or hunting) is decreased if we "slow down" tube 1. To do this, antihunt circuits are added (shown dotted in Fig. 17*I*); the antihunt actions are shown better in Fig. 17*K*. Here let us assume that points marked *S* are at steady potentials. (Although most of

* $RC = 0.1 \text{ meg} \times 0.05 \text{ mu f} = 0.005$ sec.[4-5]

these potentials change slightly as the generator voltage changes, the amount of change is small compared with the change of other potentials such as points 6 or 9.)

First watch capacitor $3C$, which is charged to the voltage between the tube-1 anode 6 and point 10 on $1R$. When increasing generator voltage makes the control-grid potential rise (as shown by arrow A in Fig. 17K), the increasing anode current lowers the 6 potential (arrow B). Capacitor $3C$ cannot instantly decrease its charge; as its 6 end lowers, its screen-grid end lowers about the same amount, so it forces the tube-1 screen

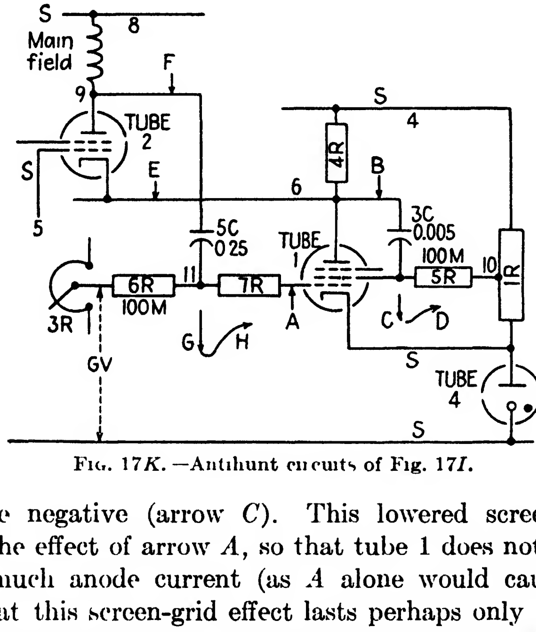

FIG. 17K.—Antihunt circuits of Fig. 17I.

grid more negative (arrow C). This lowered screen grid C opposes the effect of arrow A, so that tube 1 does not instantly pass as much anode current (as A alone would cause). But notice that this screen-grid effect lasts perhaps only $\frac{1}{5000}$ sec; $3C$ discharges through $5R$, and the screen-grid voltage returns to the point-10 potential, as shown by arrow D.

Capacitor $5C$ is added, and is charged to the potential between point 9 (tube-2 anode) and the slider of $3R$. When an increase of GV raises the tube-1 control grid (arrow A), the increased current through $4R$ lowers the tube-2 cathode (arrow E); the increased tube-2 current lowers its anode potential (arrow F). As the 9 end of $5C$ lowers, the 11 end of $5C$ instantly drops about the same amount, as shown by arrow G. (As $5C$ starts to discharge, its discharge current flows through $6R$ so that the 11

end of $6R$ becomes more negative than the $3R$ slider.) Arrow G opposes* arrow A; although GV might have increased 1 volt, point 11 drops perhaps $\frac{3}{4}$ volt (arrow G), so that the control grid rises only $\frac{1}{4}$ volt (arrow A). After perhaps $\frac{1}{30}$ sec, $5C$ has discharged through $6R$ so that point 11 returns to the potential of the $3R$ slider, as shown by arrow H. The entire 1-volt increase at GV now reaches the tube-1 control grid—but perhaps by now the amplidyne and the a-c generator have had time to reduce GV so that its correction signal is only $\frac{1}{3}$ volt instead of 1 volt.

In the above examples we see that the antihunt circuits act only when we quickly change the voltages across them. If the potential at point 6 (in Fig. 17*K*) is lowered slowly, capacitors $3C$ and $5C$ discharge slowly; the effect (at arrows C and G) is not large enough to matter. The capacitors respond to the *rate* at which the circuit voltages change.

17-12. Stabilizer or Antihunt Transformer.—Another way to correct for sudden changes in circuit voltages is to use a transformer as a stabilizer or antihunt device. Such a transformer is shown at $3T$ in the upper part of Fig. 17*I*. The primary winding of $3T$ is connected across the d-c output of the amplidyne at points 2 and 3; resistor $9R$ adjusts the effect of $3T$. Direct current flows through this primary winding, but steady d.c. cannot make a transformer produce any secondary voltage. The $3T$ secondary is connected to a third field† of the amplidyne; this field has no effect while there is no $3T$ secondary voltage However, if the amplidyne 2-to-3 voltage rises quickly, this *change* of d-c voltage across the $3T$ primary makes a voltage "kick" in the $3T$ secondary. Applied to the antihunt winding of the amplidyne, this kick produces a field strength that opposes the reference field; the total amplidyne field strength decreases, lowering the 2-to-3 voltage. Or, when the 2-to-3 voltage drops suddenly, the $3T$-secondary voltage kicks in the opposite direction, so that the antihunt field helps the reference field, raising

* There is usually no control-grid current, so both ends of $7R$ are at the same potential.

† These amplidyne fields are electrically separate, although wound together in the same slots of the amplidyne frame. Each of these fields can affect the voltage produced at terminals 2 and 3. The use of this antihunt field is described in Sec. 28-4.

the 2-to-3 voltage to normal. If the 2-to-3 voltage changes slowly, the 3*T*-secondary "kick" is too small to have any effect. The stabilizer and the antihunt field act only when the d-c voltage changes; with more or faster change of d.c., greater action results.

17-13. Controlled Buildup of Generator Voltage.—Parts of the voltage-regulator circuit of Fig. 17*J* are shown again in Fig. 17*L*, to show the added antihunt and snubber actions.

In Sec. 17-9, describing circuit conditions before there is any a-c generator voltage, we show how point 10 is so negative that tube *F* passes no current, so thyratrons 1 and 2 are "turned full on" when contactor *N* first applies anode voltage to these tubes. Now let us include the *M* contact (normally-closed) near tube *F*. While contactor *M* is not yet picked up, so there is no generator voltage, this n-c *M* contact connects around tube *F* (from anode 11 to cathode 7); current now flows through 2*R* and 11*R*, and keeps point 5 much more negative than cathode 6. Notice that capacitor 12*C* is charged to the voltage between points 5 and 10, for now there is no current flow in 4*P*, 10*R*, 9*R* or 3*P*; all parts of these resistors are at point-10 potential.

When a push button is closed, to pick up contactor *M* and apply field current to the a-c generator, this n-c *M* contact opens the circuit around tube *F*. Instantly the tube-*F* control grid rises to a new potential, which depends on the voltage-divider action of 9*R*, 10*R*, 4*P* and 2*R*. For perhaps 1/4 sec capacitor 12*C* is charging to the increasing voltage between points 5 and 10; the 12*C* charging current flows through these four resistors. Since 9*R* and 10*R* have more ohms than 4*P* and 2*R*, point 12 (control grid) is at a potential higher than midway between points 5 and 10, so this grid is higher (more positive) than cathode 7. This lets tube *F* pass current instantly when the *M* contact opens the circuit around it; this current keeps enough voltage drop across 2*R* so that point 5 does not rise suddenly or turn on the thyratron tubes 1 and 2. However, as capacitor 12*C* increases its charge, the charging current decreases, gradually lowering control-grid 12 to the potential at point 10; tube *F* gradually decreases the current through 2*R*, so point 5 rises, gradually advancing the firing point of thyratrons 1 and 2 and raising the generator voltage. By the time 12*C* has finished most of its charging action, the generator voltage has increased

so that the point-10 potential has risen and now controls tube *F* to regulate the generator voltage.

This same circuit (12*C*, 4*P*, 10*R*, 9*R*) gives antihunt action at all times. If a-c load is suddenly removed from the generator so that its voltage rises, the point-10 potential rises, to turn on tube *F*. However, 12*C* takes time to discharge and let the point-12 potential rise. Tube *F* slowly (in ¼ sec) lowers the

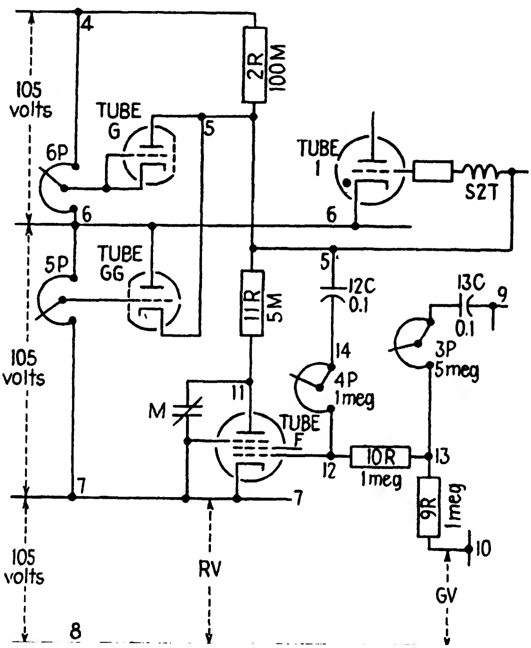

FIG. 17*L*.—Antihunt and snubber circuits of Fig. 17*J*.

point-5 potential to turn off tubes 1 and 2 and decrease the generator-field current.

At the same time, watch another antihunt circuit, which uses 13*C* and 3*P*. If the generator voltage drops (as when a-c load is suddenly added), the point-10 potential drops, but point 9 drops much faster. Since the voltage across 13*C* cannot change instantly, the change at point 9 causes a similar drop at point 13 (so that 13 is now at a lower potential than 10). At this instant, point 14 has remained at the same potential as point 10 (because of the charge on 12*C*); however, part of the voltage difference between points 14 and 13 now appears across 4*P*, letting

point 12 (control grid) instantly drop to a lower potential. Passing less current, tube F lets point 5 rise more quickly and turn on thyratrons 1 and 2. This is an "emergency" action, like the sudden tug you give the steering wheel when a front tire blows, heading you for the ditch.

17-14. Tubes May Set Limits within Which a Circuit May Operate.—In Fig. 17L, suppose we wish to prevent point 5 from becoming more than 40 volts above (more positive than) point 6, or more than 60 volts below point 6. Tube G, 6P and 5P are used for this purpose. (Tube G is a duplex tube,[7-11] having two separate triodes inside its shell. To tell them apart, let us call one triode tube G—the other triode, tube GG.) When point 5 is between these +40 and −60 volt limits, neither triode passes current. Notice that triode tube G is being used as a diode (for its grid is "tied" to its cathode). The slider of 6P is set at a point 40 volts above the lower end of 6P; therefore, the tube-G cathode is 40 volts more positive than point 6. No current can flow through tube 6 while its anode (connected to point 5) is less positive than the cathode. However, when point 5 rises to a potential slightly more than 40 volts above point 6, electrons flow from 6P slider, cathode to anode of tube G, and through 2R to point 4. This tube-G current causes enough voltage drop across 2R so that point 5 cannot rise to a potential higher than +40 volts. If the 6P slider is turned to a point 10 volts closer to point 6, then point 5 cannot rise more than 30 volts above 6P.

Similarly, triode GG is grid-controlled by the setting of 5P slider. If this 5P slider touches at a point about 65 volts below (more negative than) point 6, no current flows through tube GG until its cathode (connected to point 5) drops to about 60 volts below point 6; now the grid is only 5 volts more negative than the cathode, and this −5 grid voltage lets electrons flow from point 7, through tube F and 11R to point 5, cathode to anode of tube GG, to point 6. If tube F passes so much current that the voltage drop across 2R makes point 5 drop below the setting of 5P, the extra current passes through tube GG, instead of through 2R.

Questions

True or false? Explain why.

1. In Fig. 17B there is no circuit that lets the d-c voltage GV charge the battery.

2. In Fig. 17*B*, if generator *G* is stopped, the tube-1 grid becomes positive, so that a protective grid resistor is needed.

3. All amplifiers are electronic.

4. In Fig. 17*C*, if *GV* is always equal to *RV*, the generator voltage may change as if no regulator were being used.

5. In Fig. 17*L*, when the *M* contact is closed between tube-*F* anode and cathode, the current flowing through 2*R* is 2 milliamperes.

6. With this *M* contact closed, point 5 is 40 volts more negative than the tube-1 cathode.

7. When *M* operates, the suppressor-grid potential changes.

8. If the voltage across a capacitor is d.c., the amount of capacitor ohms becomes infinite (or like an open circuit).

9. A generator is an amplifier, since a small change in power input to the field winding causes a large change in power output from the generator.

10. When 8*R* slider (in Fig. 17*H*) is turned so that the generator output increases from 400 to 450 volts, what happens to the amount of voltage *GV*? Does it (*a*) increase 50 volts? (*b*) increase less than 3 volts? (*c*) remain unchanged? (*d*) decrease less than 3 volts? (*e*) decrease 50 volts?

CHAPTER 18

LARGE-CURRENT RECTIFIERS

Most of the circuits discussed this far use or control an amount of current small enough to be obtained from two wires or from a single phase of the a-c power supply. When more electric power is needed, for driving motors larger than 1 or 2 hp, and to produce more than 1 or 2 kw of rectified d.c., current is used from all three wires* of the three-phase a-c power supply. Such rectifiers use three or more tubes; the smoother waveshape of their d-c output is often important.

18-1. Rectifiers for Stored-energy Welding.—Many three-phase rectifiers are used in industry, to furnish power to stored-energy welders. By studying several of these rectifiers, we learn how tubes act in a polyphase circuit (a circuit that uses power from more than one phase of the a-c supply).

When a resistance weld is made with a stored-energy welding machine, no large current is taken from the a-c supply just at the instant when the weld is being made. Instead, a smaller amount of current is taken for a longer time (usually from all three wires, or phases) before the weld is to be made; the electric energy of this current is being stored in capacitors or reactors. This stored energy is then discharged through the welding transformer and into its low-voltage circuit, to make the weld. The weld is made by current which is neither a.c. nor d.c.; it is a changing current that increases to its full amount only once for each weld, and then gradually decreases to zero. Some welders seem to work better with this waveshape of welding current. Since less peak current is taken from the power feeder, the stored-energy welder does not need so large a power supply or so large feeder cables as are needed by the usual a-c resistance welder.

While electricity is storing energy, the electric current must flow in just one direction. Since alternating current (a.c.)

* Where some power companies distribute two-phase power, a large equipment uses current from three or four wires.

changes direction so often, a.c. cannot be used for storing energy for longer than a half cycle. Instead, direct current must be used for storing the energy for welding. Therefore, any kind of stored-energy welder needs a rectifier to change the a-c power supply into direct current, which can store energy gradually for several seconds if this is needed.

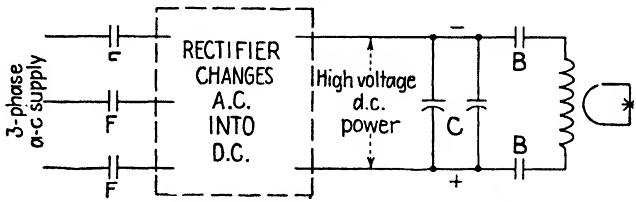

FIG. 18*A*.—Basic circuit of capacitor-discharge welder.

Many types of welding equipment store the electric energy in capacitors; Fig. 18*A* shows the kind of circuit used with such a capacitor-discharge welder. When contacts *F* connect the a-c power supply to the rectifier (whose circuit is described later[18-4]), the d.c. produced by the rectifier charges capacitors *C* to a high voltage. Contacts *F* open, and a large amount of energy is now

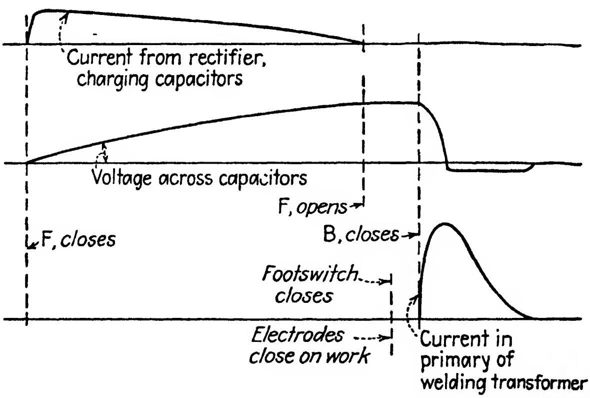

FIG. 18*B*.—Current and voltage in capacitor-discharge circuit.

stored in the capacitors. With the welder electrodes pressed onto the work, contacts *B* close; the capacitors discharge their energy into the welder by forcing current through the primary winding. As current changes in the primary, large secondary current flows through the work, making the weld. The changes in capacitor voltage and welder current are shown in Fig. 18*B*.

The capacitors are charged to 1500 to 3000 volts; because of this high voltage, a charging current of 10 to 40 amperes is enough for use with most welders. The rectifier for energy storage in capacitors has a high-voltage circuit, using thyratron or phanotron tubes.

Another type of welding equipment (called the reactor-storage,

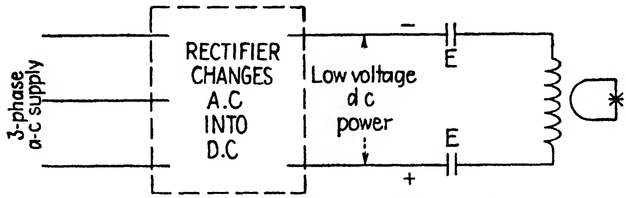

FIG. 18C.—Basic circuit of reactor-storage (Sciaky) welder.

or Sciaky, process) stores the electric energy in the inductance of a special welding transformer. In Fig. 18C the rectifier furnishes a low d-c voltage (80 to 160 volts) at all times. After the electrodes are pressed onto the work, contacts E close, and current begins to flow through the welding-transformer primary; but this does not yet make a weld. This primary current increases very slowly because of the high inductance of the welding transformer, acting like a flywheel. As it increases, the primary

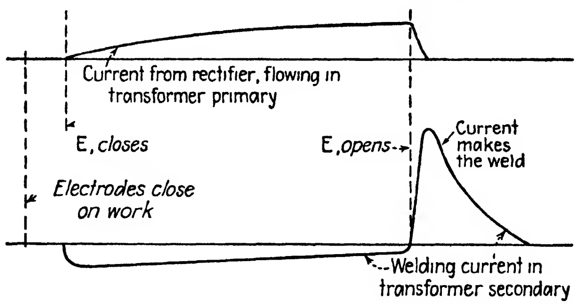

FIG. 18D —Current in reactor-storage circuit.

current gradually stores energy in the magnetic circuit (iron and large air gap) of the welding transformer. The amount of stored energy depends on the amount of this direct current, as the energy stored in a moving car depends on the car's speed. When the primary current has increased to the right amount, contacts E are suddenly opened; this stops the flow of primary current. Since the energy stored in the transformer cannot escape through

the opened primary circuit, it escapes through the closed secondary circuit by forcing large secondary current to flow, making the weld. These current changes are shown in Fig. 18*D*. Several hundred amperes of direct current are needed for this type of energy storage; the rectifier has a low-voltage circuit, using ignitron tubes.

The circuit operation of stored-energy welders is described elsewhere;* here we are interested only in the high-voltage, thyratron rectifier circuit for capacitor charging, or the low-voltage ignitron rectifier circuit. Both types may operate from three-phase a-c power; both may be phase-shifted to change the amount of d-c voltage and current output.

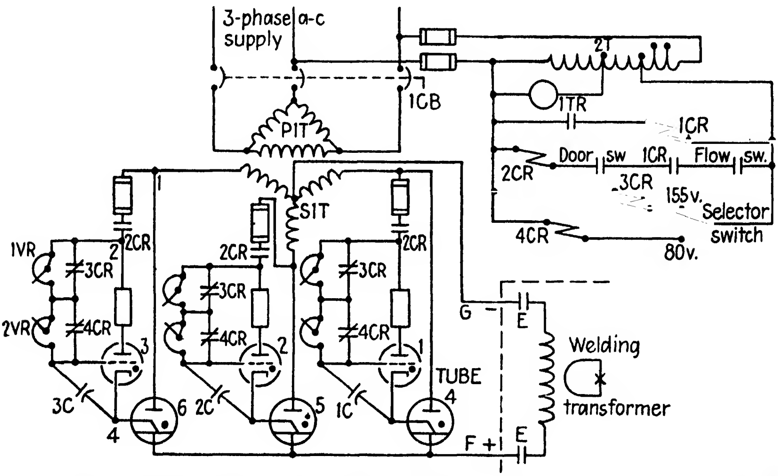

FIG. 18*E*.—Phase-shifted three-tube rectifier for reactor-storage welding (CR7503-J).

18-2. Three-tube Ignitron Rectifier (CR7503-J).—Most of the circuit of this rectifier equipment (for the reactor-storage, or Sciaky, process) is shown in Fig. 18*E*. Taking power from all three wires of the three-phase a-c supply, ignitron tubes 4, 5 and 6 change† this a.c. into a d-c voltage at terminals *F* and *G*; this voltage is fed to the welding-machine equipment. Each

* See footnote, p. 118.

† These three tubes form a three-phase, half-wave rectifier; in each of the three phases, current flows during only half of the a-c wave. A six-tube rectifier[18-4] may let current flow during both halves of the a-c wave, as it is a three-phase, full-wave rectifier.

ignitron is controlled and fired by a thyratron tube. The circuit of ignitron 6 and its thyratron tube 3 is described below and shown in Fig. 18*H*; it is exactly like the circuit of ignitron 5 and thyratron 2, or like tubes 4 and 1.

When the a-c power-supply circuit is closed, the control power passes through autotransformer 2*T* and operates time-delay relay 1*TR*. After a 5-min period for warming the thyratrons, the 1*TR* contact closes, picking up 1*CR*. If enough cooling water flows in the ignitrons, and if the rectifier doors are closed, relay 2*CR* closes its contacts (one contact in each thyratron anode circuit) to let tubes 1, 2 and 3 fire the ignitrons, to supply current to the welder as it is needed.

Suppose first that tubes 1, 2 and 3 have no grids and that each tube passes current and fires its ignitron as soon as its anode circuit will permit. Now see how ignitrons 4, 5 and 6 pass current, forced by the three-phase power supplied by anode transformer 1*T*. Figure 18*F* shows this part of the circuit alone.

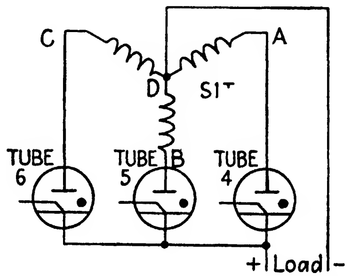

FIG. 18*F*.—Connection of ignitrons in three-phase half-wave rectifier.

The three branches, or legs, of transformer 1*T* work like three separate single-phase transformers. One leg of *S*1*T* (between *A* and *D* in Fig. 18*F*) produces a single-phase, 60-cycle a-c wave, which tries to force electrons from *D* through the load, through tube 4 to *A*. Figure 18*G* shows this voltage curve. When *A* is (+) and *D* is (−), current* can pass through tube 4; current cannot flow through tube 4 during the other half cycle, when the anode voltage is negative at *A*. In the same way, the next *S*1*T* leg (between *D* and *B* of Fig. 18*F*) produces a single-phase a-c wave, which tries to force electrons from *D* through the load and tube 5 to *B*. However, in a three-phase system, this voltage *BD* lags 120 degrees behind the voltage *AD*, as is shown in Fig. 18*G*. When *B* is (+) and *D* is (−), current can pass through

* The current waves have the shape shown in Fig. 18*G* only if the load is noninductive, such as a resistance-type furnace. The welding-transformer load is so inductive that it smooths the peaks, or ripples, into a steady current flow, as shown in Fig. 18*I*.

tube 5. Also, the third $S1T$ leg C-to-D produces a single-phase a-c wave, which tries to force current through tube 6. Figure 18G shows that the curve of voltage CD lags 120 degrees behind (to the right of) BD, but CD is 120 degrees ahead of voltage AD. When C is (+) and D is (−), current can pass through tube 6.

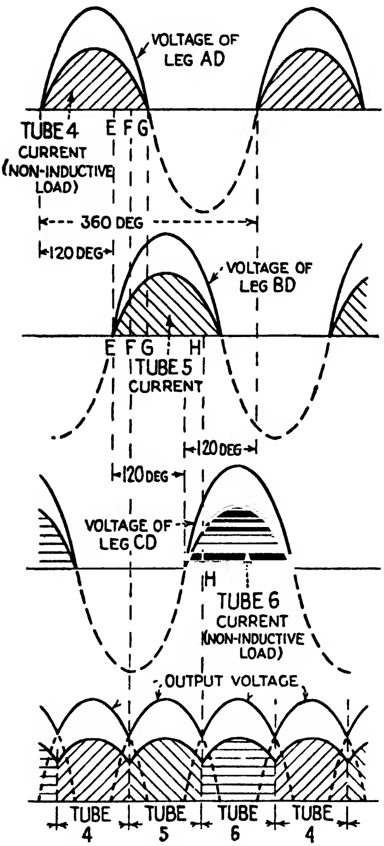

FIG. 18G.—Voltages and currents in three-phase half-wave rectifier.

Notice that tube 4 passes current, followed by tube 5, then by tube 6, then tube 4 again, etc. The electron flow through each tube passes from D (mid-point of $S1T$) through the same d-c load (the welding transformer). In Fig. 18G, between E and G, it looks as though current flows through tube 4 and through tube 5 at the same time. However, only one tube passes current at one time when tubes are connected this way and all pass current through the same load. Between E and F (Fig. 18G) notice that the anode voltage of tube 4 is higher than the anode voltage of tube 5, so tube 4 passes all the current during the time to the left of F. However, at F the anode voltage of tube 5 becomes greater than that of tube 4, so tube 5 carries all current to the right of F, until tube 5 similarly transfers the load current to tube 6 at H. Figure 18G shows that the combined output of all three tubes is a flow of direct current. The height or amount of this current is quite small when contacts E (Fig. 18E) are first closed. This current gradually increases during the time (usually less than ½ sec) while energy is being stored.

18-3. Phase-shifting the Three-tube Rectifier.*—When the three ignitrons operate as shown in Fig. 18G, they produce about 170 volts d.c., owing to the a-c voltage produced by the $S1T$ windings. To adjust this rectifier output closer to 155 volts, or to obtain only 80 volts from the same rectifier when that is desired,† a phase-shifting circuit is used to control thyratrons 1, 2 and 3, and thereby delay the firing of ignitrons 4, 5 and 6.

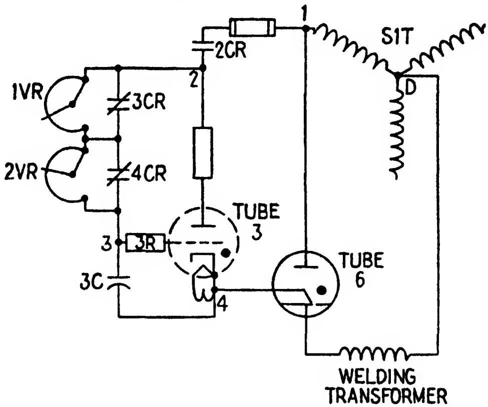

FIG. 18H.—Grid circuit for phase-shifting an ignitron (part of Fig. 18E).

The circuit of one of these tube pairs is shown again in Fig. 18H. Here if $2CR$ contact has closed, the voltage of $S1T$ is trying to force current through tube 3 and the ignitor of tube 6, so that tube 6 will permit a large electron flow from D (center tap) through the welding transformer, and cathode to anode of tube 6 to point 1. However, thyratron 3 is controlled by its own grid voltage, between points 3 and 4. This grid voltage is also the voltage drop across $3C$, which depends on the electron flow through the circuit from 4 to $3C$ and from 3 through adjustable

* This "three-tube" rectifier refers to ignitrons 4, 5 and 6 in Fig. 18E. Thyratrons 1, 2 and 3 are used merely to fire the ignitrons and are not counted in the number of rectifier tubes. If thyratrons 1, 2 and 3 are not used for firing ignitrons, but instead supply a single combined load of their own, they become the three-tube rectifier.

† This tube rectifier is often arranged to furnish d-c power to two Sciaky welding machines, interlocked so that only one machine operates at one time. By proper automatic operation of relays $3CR$ and $4CR$, one machine may receive say 155 volts for welding thick metal parts, while the other machine welds smaller parts a moment later, receiving a lower voltage from the same rectifier.

resistor $1VR$ or $2VR$ to point 2. (This $3C$ capacitor is not merely the small grid-to-cathode protective device[12-7] used so often in previous circuits. Here $3C$ is larger, 1 mu f, and helps to control tube 3.) To make the rectifier furnish 155 volts to the welder, relay $3CR$ is picked up by a selector switch in the upper right portion of Fig. 18E. This opens the $3CR$ contact in Fig. 18H, inserting the resistance of $1VR$ into the tube-3 grid circuit. However, to make the rectifier furnish only 80 volts to the welder, the selector switch is closed so as to pick up $4CR$. This opens the $4CR$ contact instead (in Fig. 18H), inserting the larger resistance of $2VR$ into the tube-3 grid circuit. At the same time, other $4CR$ contacts are controlling the grids of tubes 2 and 1 in the same way. Let us see how these resistances of $1VR$ and $2VR$ phase-shift tubes 1, 2 and 3, to change the rectifier output voltage.

If the contacts of $3CR$ and $4CR$ could be closed at the same time (in Fig. 18H), the grid of tube 3 is connected (through protective resistor $3R$) to the tube-3 anode at point 2. The grid becomes positive at that instant when the tube-3 anode voltage crosses the 0 line; this is shown at J in the upper curve of Fig. 18I. However, tubes 3 and 6 cannot pass current earlier than point K, for the preceding ignitron 5 is carrying all the load current until K (where the voltage of transformer leg CD becomes greater than leg BD). Notice that, even if the phase of the tube-3 grid voltage is delayed 30 deg, so that it does not become positive until K, it does not affect the firing of tube 3.

If contact $3CR$ is open, the resistance of $1VR$ is now in series with capacitor $3C$. Part (b) of Fig. 18I shows how the arrow of alternating current I (flowing in this $1VR$-$3C$ grid circuit of tube 3) leads the tube-3 anode-voltage arrow CD by the angle L, or less than 90 deg. Since the voltage across capacitor $3C$ is always 90 deg behind current I, this $3C$ voltage now lags behind CD by the angle M; the tube-3 grid does not become positive until point N. At N tube 3 passes current, which fires ignitron 6. Notice that the preceding ignitron 5 has continued to carry the load current until point N; the voltage applied to the load has been decreased somewhat, since the sections P have been lost by the delayed firing of the tubes. We see that $1VR$ may be set so that the remaining load voltage is perhaps 155 volts, as is desired for the operation of one welding machine.

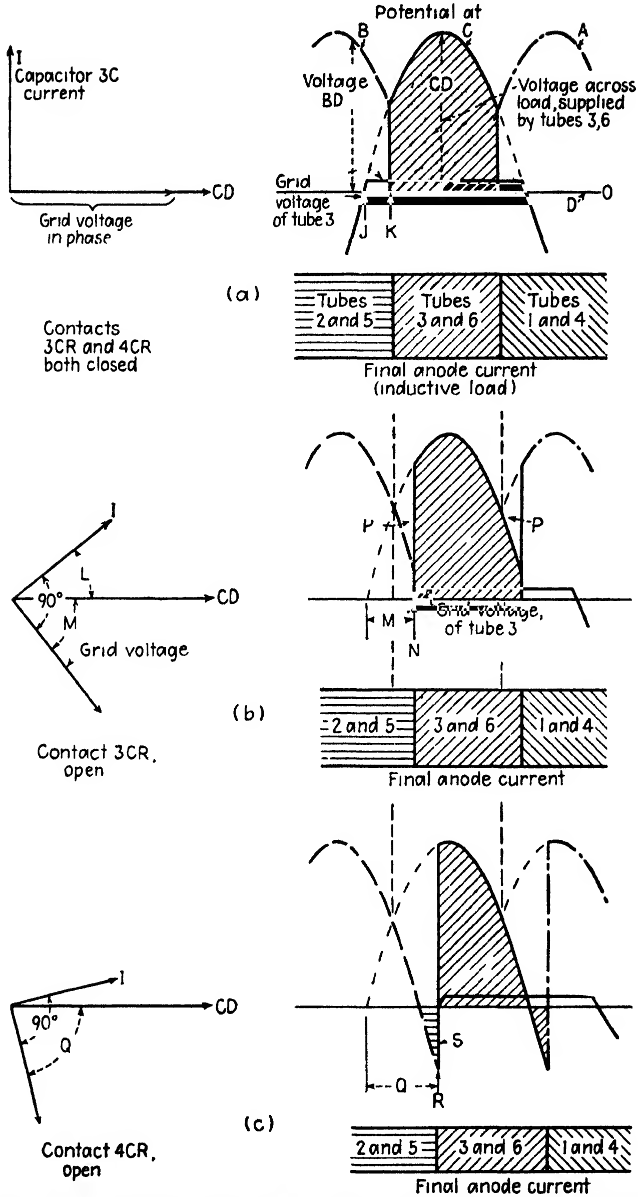

FIG. 181.—Waveshapes in three-tube rectifier when phase-shifted to decrease the output voltage.

If contact $4CR$ is open, the resistance of $2VR$ is now in series with capacitor $3C$; this $2VR$ resistance is greater than that of $1VR$, and is set to produce lower rectifier voltage. Part (*c*) of Fig. 18*I* shows that the current I now leads the anode voltage CD very slightly; the tube-3 grid voltage (across $3C$) lags by the angle Q, so tube 3 does not fire ignitron 6 until point R. The preceding ignitron 5 has continued to carry the load current until point R, although this applies a reversed or negative voltage to the load, as shown at S. The rectifier now produces a jagged voltage wave whose average height is less than before; this reduced voltage forces less current through the inductive load of the welding transformer.

18-4. A Six-tube (Three-phase, Full-wave) Rectifier.—Figure 18*J* shows the main parts of a rectifier that supplies high-voltage

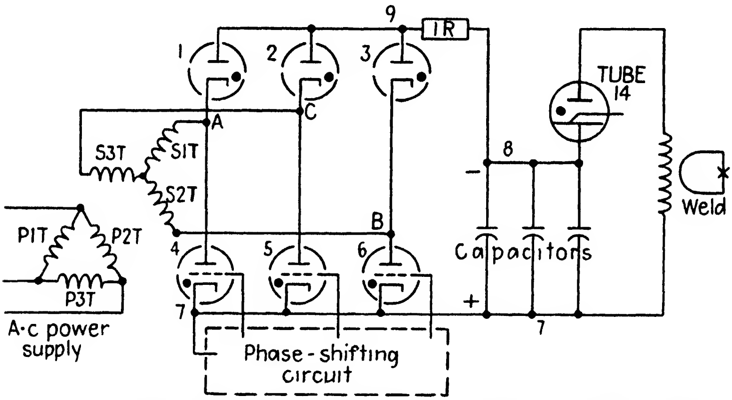

FIG. 18*J*.—Three-phase full-wave rectifier for capacitor-discharge welding.

d.c. for charging capacitors used in a stored-energy welding equipment. After the capacitors are charged, tube 14 is fired to let the capacitors discharge through the welding transformer, thus producing the weld. Notice that six hot-cathode tubes are used in the rectifier; only three of these are grid-controlled. The anode transformer has three secondary legs (like $S1T$ in Fig. 18*E*), but no wire connects to its center tap. These three legs are numbered like three separate transformers $1T$, $2T$ and $3T$; these furnish three-phase power at terminals A, B and C. Although there are only three a-c voltage waves (as shown in Fig. 18*G*), we shall find that the d-c output voltage of this rectifier (between points 7 and 9) has six peaks, or ripples, during each

complete cycle of the a-c power supply, as shown in Fig. 18*M*. To see what causes these six peaks, first notice that tubes 4, 5 and 6 alone would operate like the three-tube rectifier of Sec. 18-2, producing a voltage wave like Fig. 18*G*. Figure 18*K* shows the waves of a-c voltage produced by the secondary windings *S1T*, *S2T* and *S3T* in Fig. 18*J*. Starting with the winding between *A* and *B*, curve *AB* (in Fig. 18*K*) shows the voltage wave when *A* is (+) and *B* is (−). During the next half cycle, when *A* is (−), the continuing curve *BA* is shown dotted below the straight 0–0 line. Transformer lead *A* is connected to the anode of tube 4, which passes current while curve *AB* is above the line, but it cannot pass current while curve *BA* is below the line. Similarly, curve *BC* is the voltage wave (appearing between transformer terminals *B* and *C*) when *B* is (+) and *C* is (−) and current can pass through tube 6; curve *CA* shows the

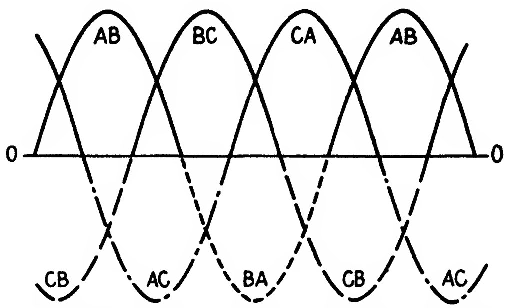

FIG. 18*K*—Voltage waves of three-phase transformer in Fig. 18*J*.

voltage between terminals *C* and *A* when *C* is (+) and *A* is (−) and current can pass through tube 5.

Now see what happens when all six tubes are used. During the peak of curve *AB*, electrons start from negative terminal *B* and pass upward through tube 3 and 1*R* to point 8 and to the capacitors. Returning from 7 (positive side of capacitors), electrons pass through whatever thyratron completes the circuit to terminal *A*; this is seen to be tube 4. Place this information in Fig. 18*L* by marking 3-4 above peak *AB*, showing that current flows through tubes 3 and 4 at this part of the wave. Still using transformer terminals *A* and *B*, but a half cycle later, when *A* is (−) and *B* is (+), electrons cannot flow in the reverse direction, down through tubes 4 and 3. However, notice that elec-

trons can now flow from *A* up through tube 1 and 1*R* to the capacitors, returning through tube 6 to *B*. This shows that electrons flow in the same direction to the capacitors, even during the peak of wave *BA* (below the straight line in Fig. 18*K*). To show this rectifier action, in Fig. 18*L* we can turn curve *BA* upside down to a new place above the straight line, but crossing it at *T* and *U*, the same as before. During this peak *BA*, electrons flow through tubes 1 and 6, so 1-6 is marked above peak *BA*. (Notice that peak *BA* takes its place halfway between peaks *BC* and *CA*.) In the same way, if we follow the voltage wave between transformer terminals *B* and *C*, we shall see that

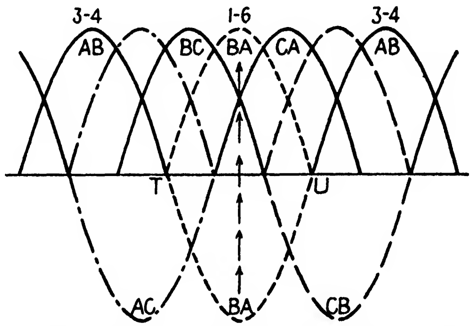

FIG. 18*L*.—Voltage waves moved above the line by rectifier action.

electrons flow from *C* (−) through tube 2 to capacitors, returning through tube 6 to *B* (+); a half cycle later, they flow from *B* (−) through tube 3 to capacitors, returning through tube 5 to *C* (+).

Figure 18*M* shows the final result. Notice how the tubes transfer the current load from one to the other (in much the same way that a man shifts his weight from one foot to the other while walking). For example, at *X* tube 2 continues to fire, but the load is transferred from tube 4 to tube 6; at *Y* (60 degrees later) tube 6 still continues to fire, but the load is shifted from tube 2 to tube 1. Each tube may pass current steadily during two of these voltage peaks; the shaded part of Fig. 18*M* shows that tube 3 is passing current during the voltage peaks *CB* and *AB*. Current may flow in any tube during 120 deg or one-third of each cycle.

At every instant, one phanotron and one thyratron are connected in series, so that the same current flows through both; if

we grid-control one of this pair, we may control the current flowing through both tubes. The rectangle in Fig. 18*J* contains circuits (not shown) that phase-shift tubes 4, 5 and 6; we are interested only in the result—the effect on the voltage produced by this six-tube rectifier.

In Fig. 18*M*, even if tube-6 grid becomes positive at *W* (at the start of the voltage wave whose peak is *BC*), notice that tube 6 cannot pass current until *X* (60 deg. later) or until tube 4 stops passing current. Therefore, the tube-6 grid may be phase-shifted as much as 60 deg without affecting tube 6. However, if the grids of tubes 4, 5 and 6 are phase-shifted about 100

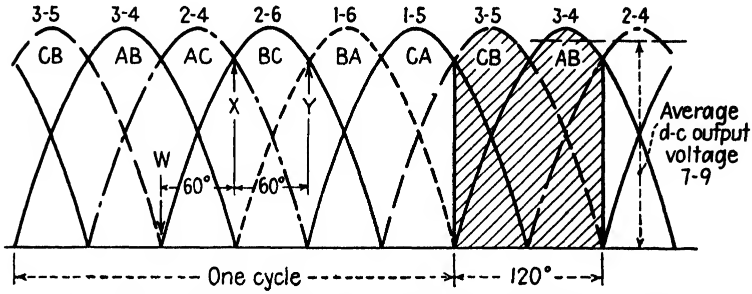

FIG. 18*M*.—Output-voltage wave of three-phase six-tube rectifier.

degrees, Fig. 18*N* shows the result—a jagged output voltage wave, whose average height is lower than in Fig. 18*M*. In (*a*) of Fig. 18*N*, the curves show the rectifier output when it is supplying a resistance load, or when it is starting to charge a capacitor that has not yet built up any voltage.

18-5. Effect of Capacitor Voltage on Rectifier Output.—When the three-phase rectifier of Fig. 18*J* has charged the capacitors to say 2000 volts d.c., more current cannot flow into the capacitors except when the rectifier voltage 7-to-9 is greater than 2000 volts. This is shown in (*b*) of Fig. 18*N*; only the shaded part of the rectifier voltage can force current to flow—the rest of the rectifier voltage is offset or bucked by the capacitor voltage. Charging current flows only in pulses, as at *F*. At point *G* (where the charging current stops), the tubes have disconnected points 7 and 9 (of Fig. 18*J*) from the transformer terminals *A*, *B* and *C*; the d-c capacitor voltage now appears between points 7 and 9 until a tube again fires, at *H*.

As shown in (*b*) of Fig. 18*N*, the capacitor charge or back-

voltage opposes the anode-transformer voltage so that only the difference (shaded portion) appears across the tubes. If the amount of this voltage (I in Fig. 18N) is larger than about 15 volts, it is enough to make these hot-cathode tubes pass current.*

To store enough energy, the capacitors (Fig. 18J) are charged to high voltage, which appears between points 7 and 9. Since a thyratron and a phanotron always operate together across this voltage, only half of this high voltage appears between anode and cathode of any single tube.

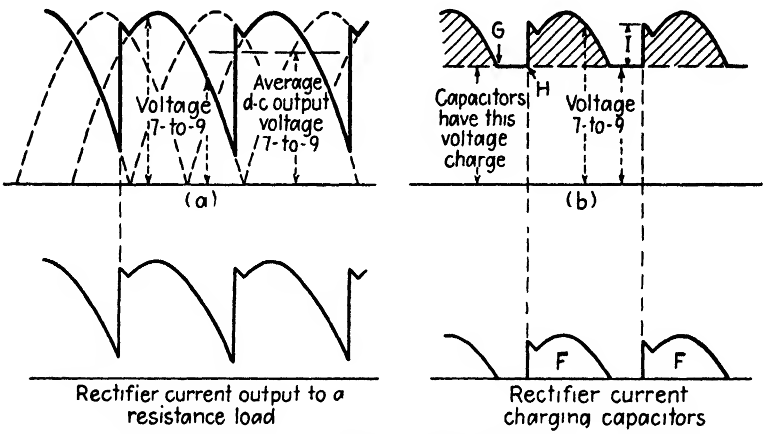

FIG. 18N.—Waveshapes of rectifier of Fig. 18J at decreased output.

18-6. A Six-tube (Six-phase, Half-wave) Rectifier.—Still supplying-three phase power to the anode transformer, Fig. 18O shows how six tubes may be connected to work as a six-phase rectifier. The anode transformer has three secondary windings (AE, DC and BF), each of which has a center tap; the three center taps are connected together, and they also are connected to N, the negative side of the d-c load. This forms the six-ended "snowflake" shape shown in the upper part of Fig. 18O. Without any connection's being changed, these secondary windings are shown again in two groups, making them look like six separate windings, each having one end connected to N. The other ends

* These thyratrons cannot be replaced by ignitron tubes in this circuit, if this small voltage I is used also as the ignitor voltage; at least 100 to 150 volts is needed for an ignitor circuit. Ignitrons cannot work as rectifiers to supply a capacitor or a d-c motor-armature load, unless the circuit is arranged as described in Sec. 18-9.

of these windings connect to the six tube anodes. All six cathodes are connected together and to the positive side of the d-c load.

Figure 18*P* shows how each of the six parts of the anode-trans-

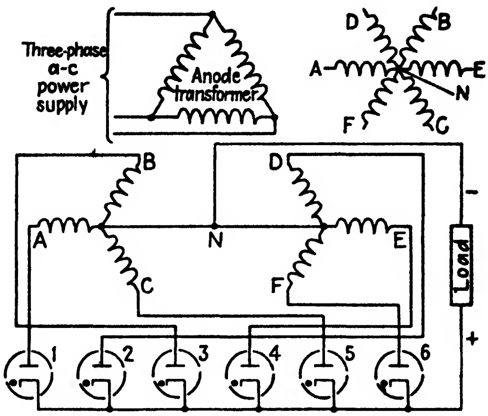

FIG. 18*O*.—Six-phase half-wave rectifier.

former secondary produces a complete a-c voltage wave, so that there are six separate waves during each cycle of the power supply. Since a rectifier tube is connected to each of the six

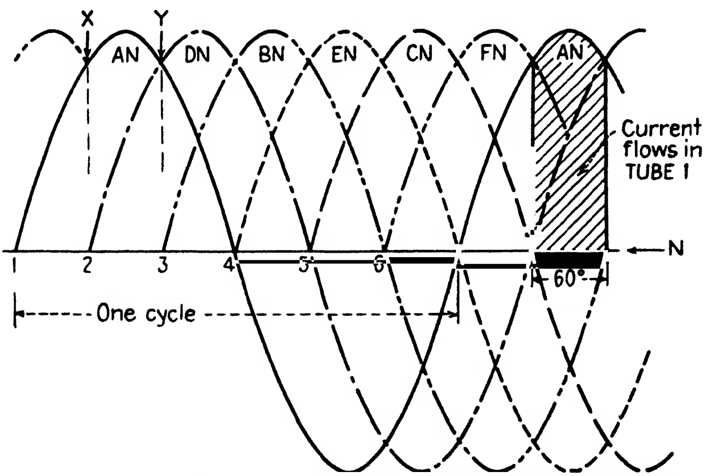

FIG. 18*P*.—Transformer voltages supplied to six-phase rectifier of Fig. 18*O*.

ends of the windings, current may flow during only one half of each a-c wave; the halves below the *N* line in Fig. 18*P* are not used, for they make the tube anodes more negative than *N*.

The output waveshape of this rectifier (shown by the line along the tops of the voltage waves in Fig. 18*P*) is the same as in Fig. 18*M*.

In Fig. 18*O*, tube 1 passes current only when transformer terminal *A* is more positive than any other terminal. Figure 18*P* shows that this happens near the top of the *AN* voltage wave; between *X* and *Y*, electrons flow (in Fig. 18*O*) from *N* through the load and return through tube 1 to *A*. In the six-phase rectifier, notice that current flows through only one tube at any instant; the whole *A*-to-*N* transformer voltage appears across the load and just one tube. Each tube handles the whole load current during 60 degrees or one-sixth of each cycle.

18-7. Six-tube Rectifier with Interphase Transformer.— This rectifier (shown in Fig. 18*Q*, and called a double-*Y* three-phase

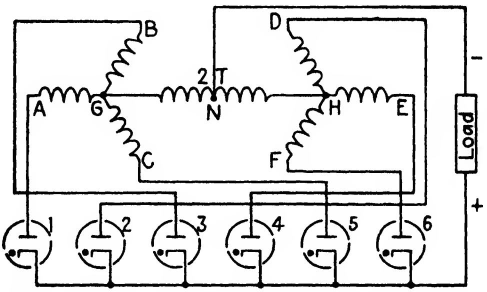

FIG. 18*Q*.—Six-tube rectifier with interphase transformer 2*T*.

half-wave rectifier) has the same circuit as Fig. 18*O*, except that an interphase transformer 2*T* is added between *N* and the center taps *G* and *H*. This transformer 2*T* has large inductance; to show its effect, Fig. 18*R* includes an enlarged picture of the rectified voltage near the peaks. At point *Y* (which is the same as *Y* in Fig. 18*P*), when the current through tube 1 decreases (to let the tube-2 current increase), the current through the 2*T* leg *G*-to-*N* must also decrease. The inductance of 2*T* reacts to this decreasing current by producing a voltage (shown at *R* in Fig. 18*R*) that prevents voltage *AN* from decreasing so fast; instead, the potential of tube-1 anode is made to follow the curved line from *Y* to *S*. This sudden voltage *R* in the *G*-to-*N* leg makes a similar voltage *L* appear across the *N*-to-*H* leg of 2*T*; this voltage *L* (in Fig. 18*R*) prevents voltage *DN* from rising so fast. Instead the potential of tube-2 anode is also made to

follow the curved line Y to S. Since the anode voltages of tube 1 and tube 2 are now equal, both of these tubes may pass current at the same time. Not until S does the tube-1 current stop; this tube-1 current shifts to tube 3. Meanwhile, tube 2 continues to pass its half of the load current until T, where it is shifted to tube 4.

When the interphase transformer is added, the load current is made to divide between two tubes.* Each tube needs to carry only half as much current as it would carry in the six-phase circuit of Fig. 18*O*, but it must carry this current for ⅓ cycle instead of ⅙ cycle. The output voltage of this rectifier (*ST* in Fig. 18*R*) still has six peaks, or ripples, during each cycle.

The tubes shown in Figs. 18*O* and 18*Q* are simple phanotrons. By using thyratrons instead, either kind of six-tube rectifier may be phase-shifted to give variable d-c output voltage. Large

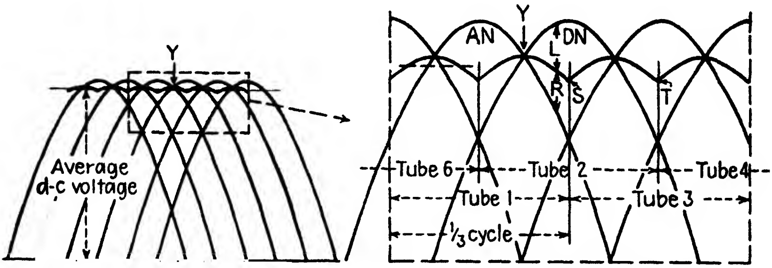

FIG. 18*R*.—Waveshapes of rectifier with interphase transformer.

power rectifiers that deliver more than 50 kw output may have similar circuits; they generally use ignitron tubes specially designed for rectifier service. Such a six-tube power rectifier is discussed later.[18-9] First let us see how such ignitrons may be used to supply direct current to the armature of a large d-c motor, which needs more current than is usually furnished by thyratrons.

18-8. Ignitron Rectifier for Motor-armature Supply.—Figure 18*S* shows ignitron tubes 1, 2 and 3, which are used as a three-phase half-wave rectifier. (Although a similar circuit is shown in Fig. 18*E*, that rectifier is used with a welding transformer; such a load has no back voltage, so the ignitrons are fired by thyratrons that operate from the same anode transformer.) The

* Anode reactors also permit several vapor-filled tubes to share the total load; without such anode inductance, one of the vapor-filled tubes takes all or most of the load current.

complete circuit for firing ignitron tube 2 is shown; the same kind of circuit is used with tube 1 and with tube 3.

A rectifier-type ignitron is used in Fig. 18*S*; it differs from welder-type ignitrons[9-6] because it has a holding or auxiliary anode, baffles or shields inside to oppose arc back, also two ignitors, one of which is merely a spare.

Only the main anode of the ignitron is connected to the three-phase anode transformer; the ignitor circuit has a separate voltage supply all its own, and the holding anode has another separate supply. Even when the main anode voltage is so low that no

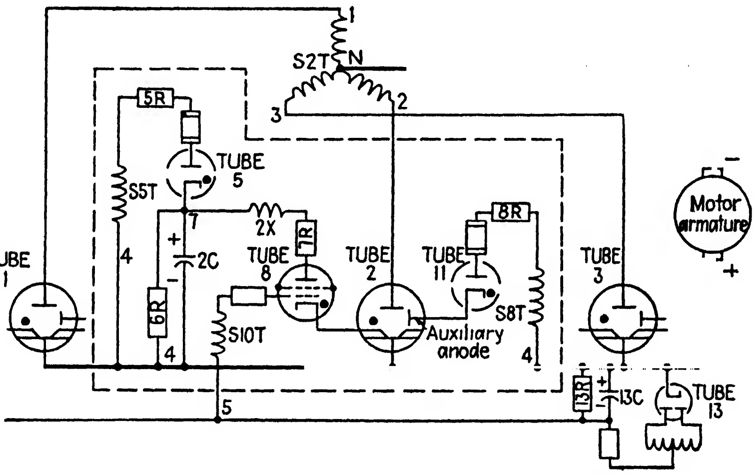

FIG. 18*S*.—Ignitron rectifier for motor-armature supply.

current flows in this main anode or in the motor armature, the ignitor still fires the ignitron; current still flows through the holding-anode circuit.

In Fig. 18*S*, phanotron tube 5 and thyratron 8 control the large current pulse needed for firing ignitron 2. This electricity comes from transformer *S5T*. Tube 5 is a half-wave rectifier, which lets the *S5T* voltage charge capacitor 2*C* to about 300 volts; electrons flow from terminal 4 of *S5T*, up through 6*R*, tube 5, fuse and 5*R*, back to *S5T*. The voltage drop across 6*R* charges 2*C*. Whenever thyratron 8 is fired, the charge in 2*C* forces electrons to flow from 4, cathode to ignitor of tube 2, cathode to anode of tube 8, through 7*R* and 2*X* to 7. This discharge current is large enough to fire ignitron 2; 2*C* discharges so

quickly that this current pulse lasts only $\frac{1}{20}$ cycle. Reactor $2X$ prevents this discharge current from increasing too fast. Once each cycle tube 2 is fired in this way. Capacitor $2C$ is then recharged through tube 5, ready for the next cycle.

During most of each cycle, tube 8 is kept from firing, because its grid is connected to point 5; rectifier tube 13 produces a voltage across $13R$ (filtered by $13C$), which keeps point 5 perhaps 50 volts more negative than point 4 (which is the cathode potential of tube 8, since there is now no voltage drop across the tube-2 ignitor). To fire tube 8, grid transformer $S10T$ is energized by another tube circuit (which is not shown, but which may be similar to circuits described in Chap. 26). $S10T$ gives a voltage pulse that drives the tube-8 grid more positive than point 4; this happens at the desired point in each cycle.

Earlier (near the beginning of each positive half-cycle of tube-2 anode voltage), the voltage produced by $S8T$ becomes positive at the end nearest tube-11 anode; the holding anode is now more positive than the pool cathode and terminal 4. As soon as tube 8 lets $2C$ discharge through the tube-2 ignitor, $S8T$ forces electrons to flow from terminal 4, cathode to holding anode of tube 2, through tube 11, fuse and $8R$ to $S8T$; this flow is steady for the rest of that half cycle. Since these electrons are already flowing in tube 2 and the holding anode, the main anode of tube 2 may also pass current (even a part of an ampere) whenever the anode-to-cathode voltage is greater than 15 volts. In this way, ignitron 2 now behaves like a thyratron and may be used in motor-armature circuits usually supplied only by thyratrons.

18-9. Magnetic-impulse Firing of Ignitron Rectifier.—Large ignitron rectifiers often supply d-c loads of 75 to many thousand kilowatts, using three or more of the rectifier-type tubes. The circuit arrangement of such a six-tube rectifier is shown in Fig. $18T$; these tubes are connected to the six-phase transformer $1T$ and the interphase transformer $2T$, as shown in Fig. $18Q$. Of special interest in Fig. $18T$ is the circuit inside the dotted rectangle, which is used for firing ignitrons 3 and 6; two duplicate circuits are used to fire the other ignitrons. All these firing circuits receive a-c power from control (auxiliary) transformer $3T$; solid lines show the parts used mainly with tubes 3 and 6. The holding anodes of the ignitrons receive power from the six-phase $S3T$ winding (above tube 6).

The one firing circuit (in the large rectangle in Fig. 18T) may be used with both tubes 3 and 6 since these tubes use the same phase of the three-phase power supply; the anode voltage of tube 3 is opposite to (or 180 deg. out of phase with) the tube-6 anode voltage. The rectangle circuit fires tube 3 at the desired time; then ½ cycle later it fires tube 6. In this firing circuit no tubes are used; the sudden ignitor-current impulse comes entirely from devices that are not electronic. Because the

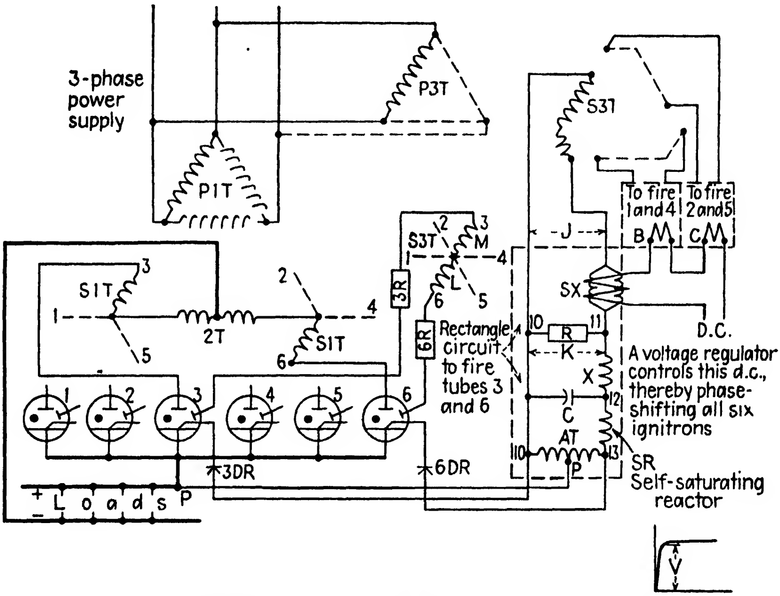

FIG. 18T.—Magnetic-impulse firing of six-phase ignitron rectifier.

$S3T$ voltage includes a portion from several phases, the voltage-J input to the rectangle lags about 20 deg behind the tube-6 anode voltage. This voltage J is connected across resistor R* and a saturable reactor SX, to form a phase-shifting circuit. With no direct current flowing in SX, the voltage K lags about 45 deg behind voltage J. By increasing the d.c. in SX, the voltage K is brought closer in phase with J; since this advances the firing point of the ignitrons, an increase of this d.c. in SX will increase the voltage output of the 6-tube rectifier.

* In the complete firing circuit, R is often replaced by a capacitor and a constant reactor in series.

Starting now with the a-c voltage K, first let us watch how ignitron tube 6 is fired. During the half cycle of K voltage when point 11 is more positive than 10, capacitor C becomes charged by electrons flowing from 10 into C, through reactor X to 11. This C voltage is positive at point 12; it increases slowly within the half cycle because reactor X does not permit the charging current to increase suddenly. Before this C voltage is near its largest amount, the reactor SR has so much inductance that C voltage can force only a small flow of electrons from 10 through the left side of autotransformer AT to mid-point P, from cathode to ignitor of tube 6, through disk rectifier 6DR to point 13, through SR to 12. This current is too small to fire tube 6. However, SR is carefully built of special metal (such as Nicoloi), which saturates suddenly when the voltage across it reaches a certain value (as shown on its saturation curve at V in Fig. 18T). When the voltage across capacitor C becomes greater than this value V, suddenly SR loses most of its inductance and cannot prevent a change of current through it. Capacitor C now discharges, forcing large current to flow through the tube-6 ignitor and SR; this current fires tube 6. As C discharges quickly, its voltage drops to less than V and lets SR regain its high inductance; the large ignitor current flows for less than $\frac{1}{20}$ cycle. This is long enough to fire tube 6; the voltage L (one leg of $S3T$) now forces electrons to flow from the pool cathode to the relieving anode and through 6R. This current flows for the rest of the half cycle of M voltage; any time after this holding-anode current starts, current may flow also through the main anode of tube 6 for as much as $\frac{1}{3}$ cycle before ignitron 2 fires. All the above actions happen within the half cycle while voltage K is more positive at point 11.

During the next half cycle, the voltage K reverses (in the rectangle circuit of Fig. 18T), so that point 10 becomes more positive than 11; slowly capacitor C charges to this new voltage. This C voltage forces a small flow of electrons from 12 through SR, through the right-hand side of AT* to mid-point P, from cathode to ignitor of tube 3, through disk rectifier 3DR to point 10. When the C voltage becomes larger than V, SR saturates

* Notice here that disk rectifier 6DR prevents the flow of electrons from 13 in the reverse direction (ignitor to pool of tube 6), which might damage the ignitor of tube 6.

and permits much larger electron flow through this same path, firing ignitron 3. At once, voltage M forces electrons to pass from the tube-3 pool to the relieving anode and through $3R$.

Only the firing of tubes 6 and 3 is described above. After tube 6 is fired, tube 1 is fired (60 deg or $\frac{1}{6}$ cycle later) by a separate rectangle-B circuit; then tube 2 also is fired (by rectangle C) before tube 3 is fired. The three rectangle circuits take turns in firing their ignitrons; each rectangle circuit fires two tubes, 180 deg or $\frac{1}{2}$ cycle apart.

To decrease the output voltage of the rectifier, the amount of direct current is decreased in SX and the two duplicate saturable reactors in rectangles B and C; all six ignitrons now receive their ignitor-current pulses later in the cycle.

Questions

1. Which of the following examples use a type of energy storage similar to the energy stored in a transformer?

a. The Christmas-club plan of a savings bank
b. Hammering a nail
c. The flywheel on a punch press
d. An air rifle
e. Beating a rug
f. An air hose
g. A water tank high above ground
h. Batting a ball
i. A crowbar
j. A handsaw

True or false? Explain why.

2. If tubes 4, 2 and 6 are removed from the six-tube rectifier of Fig. 18O, the output waveshape becomes the same as in Fig. 18G.

3. The firing point of ignitrons (in each half cycle) cannot be controlled accurately unless tubes are used for controlling the ignitor current.

4. Only a six-phase rectifier has six ripples per cycle.

5. Four tubes may be connected so that their output voltage has either four ripples per cycle, or two per cycle.

6. If the firing of each tube of a six-phase rectifier is delayed the same amount, no tube can be delayed more than 120 deg.

7. In a three-phase rectifier, if one tube loses its grid voltage, that tube may pass current for a half cycle, or 180 deg.

8. In Fig. 18J, if the phase-shifting circuit always fires tubes 4, 5 and 6 at 90 deg lagging, the same amount of tube current flows, whether the capacitors have 1500 volts' charge, or zero charge.

CHAPTER 19

HIGH FREQUENCIES AND SHORTER WAVELENGTHS

All the circuits studied this far use d.c., or they use a.c. at a power-supply frequency, such as 60 cycles per second. Many electronic circuits in industry operate at much higher frequencies; many kinds of electron tube may be made to produce a.c. that changes direction millions of times each second. Today we have radio, induction heating, fluorescent lights and X rays because electron tubes can make such very high frequencies or oscillations. The secret of success of these fields of electronics is due to the high frequencies themselves; if we could produce such high-frequency a.c. by other devices besides electron tubes, we could still have radio,* X rays, etc. Since various kinds of electron tube can help to produce these very high frequencies so easily, or can respond to them, we include the results in the study of electronics.

We read or hear so much about the wonders of electronics, where we find words or names such as microwaves, megacycles, ultraviolet, X-ray diffraction, artificial fever, FM, uhf, short-wave radio, television, supersonics, infrared and angstrom units. Although many of these apply to the field of communications and broadcasting, yet electronics in industry makes similar use of these ideas or terms. Many industrial problems are being solved by using electronic circuits once used only in radio. Therefore, this chapter includes basic thoughts along these lines, to supply some of the knowledge usually obtained in the study of physics. Also since electronics is used in problems of sound, heat, and light, we need to know the nature of these things.

19-1. The Frequency Spectrum.—To understand many parts of electronics, we must know how electricity behaves at higher frequencies. Besides flowing as electric current in a wire or through a tube, electricity sends an impulse or a signal through

* Early radio used no electron tubes, but produced the needed high frequency by arc gaps. X rays produced by electron tubes give about the same result as radium, the rare material made by nature.

space perhaps for thousands of miles. Electricity that reverses a million times per second can cause results far beyond what the same electricity can do at 60 cycles per second. This effect that electricity produces out in space is called *electromagnetic radiation.**

What many people may not know is that this electric signal through space (which gives us radio, induction heating or artificial fever) is exactly the same thing as a beam of light or X rays, or heat from the sun, except that the frequency is different. Any light that we see (whether it is sunlight or comes from a lamp) is really a radiation or movement of energy through space; it is vibrating about a million billion times per second. A human eye responds to this kind of energy signal and we call it light. If this same kind of energy passes through space but vibrates only one-tenth as rapidly as the light ray, the eye cannot see it but we can feel it—it is now the kind of energy signal that we call heat. Vibrating at these frequencies of light and heat, we do not say that this energy is electrical; yet it was proved 20 years ago that the only difference between a ray of light and a radio electrical beam is in its frequency, or rate of vibration. Since it is known that all these kinds of radiation (light, heat, radio, ultraviolet, X ray, etc.) differ only in frequency or wavelength, we can show and study them better by putting them on a chart; the entire range of these known frequencies is called the *frequency spectrum* or the *ether spectrum.* Such a chart is shown in Fig. 19*A*. Even a 60-cycle alternating current may produce a radiation of energy through space (which we also call its *magnetic field*); such a radiation is shown at the left-hand or low-frequency end† of Fig. 19*A*, at the point marked *A*.

Between *A* and *C* on this chart is a part marked "Sound." A sound we hear is not a radiation of electricity through space; instead, sound is the effect on our ears caused by a vibration passing through the air.‡ However, this sound vibration has a

* For more complete description of such radiation, see Don P. Caverly, "A Primer of Electronics," Part III, McGraw-Hill Book Company, Inc., New York, 1943.

† Sometimes the spectrum chart is arranged so that the low-frequency end is at the right; tracing along such a chart from left to right, the wavelength increases. Tracing from left to right in Fig. 19*A*, the frequency increases and the wave length decreases..

‡ If an electric doorbell is placed inside an airtight glass tank, the sound

frequency of about 30 to 10,000 cycles per second; we include sound in Fig. 19*A* (even though it is not an electromagnetic radiation) to complete the picture of those things that we recognize or know by their frequency or rate of vibration.

19-2. Figures on the Spectrum Chart.—To be able to include the frequencies of these known kinds of electromagnetic radiation, the chart of Fig. 19*A* must reach from 1 cycle per second up to 1,000,000,000,000,000,000,000,000 cycles per second. To make this possible (and still be able to show useful figures at each part of the chart), we use a logarithmic scale; with such a scale, each time we move one division to the right on the top scale, the number of cycles has increased 10 times. (Notice that the 1000-cycle mark is two divisions from the 10-cycle mark.)

Above 1000 cycles (and through part of the radio range), the frequency is given in kilocycles. Each kilocycle is 1000 cycles (as shown in the following table so the point marked 100 kc

Prefix	Meaning	Example
micro	$\frac{1}{1,000,000}$, or 0.000001, or 10^{-6}	Microwatt
milli	$\frac{1}{1000}$, or 0.001, or 10^{-3}	Milliampere
centi	$\frac{1}{100}$, or 0.01	Centimeter
hecto	100	Hectowatt
kilo	1000, or 10^3	Kilowatt, kilocycle
mega	1,000,000, or 10^6	Megawatt, megacycle

is also 100,000 cycles. Similarly, a million cycles is called a megacycle, so 10 Mc is the same as 10 million cycles, or 10,000 kc. (At point *E* in Fig. 19*A*, the frequency of 300,000,000 cycles per second can also be called 300 Mc or 300,000 kc.) At still higher frequencies, instead of using "millions of megacycles" or "trillions," etc., values of wavelength are more often used, as described later. However, these huge numbers of cycles may

of the bell may be heard by a person outside the tank as long as enough air is left inside the tank; the air carries the sound vibrations from the bell to the wall of the tank. However, when the air is pumped out of the tank (producing a vacuum), the bell is no longer heard, although it is still seen to be moving.

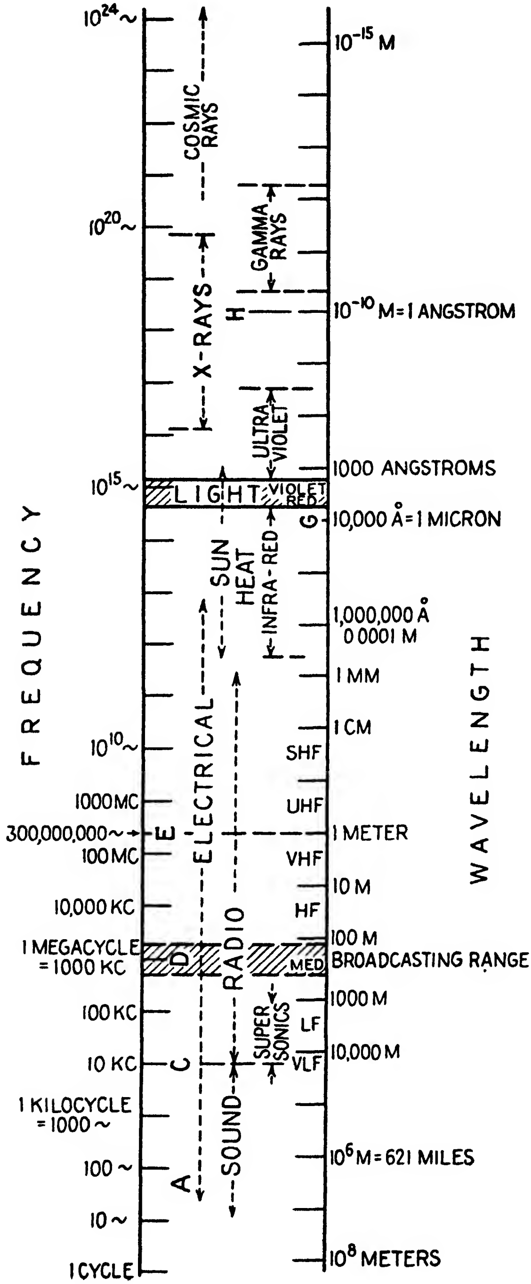

FIG. 19A.—Spectrum of frequencies and wavelengths.

also be shown as 10^{15} or $10,^{20}$ etc.* To show the size of these numbers in the upper right-hand part of Fig. 19*A*, let us realize that if the entire national debt of the United States is $1,000 billion or $1,000,000,000,000, it is merely $\$1 \times 10^{12}$. So the number of cycles per second in a light beam is ten times greater than the number of pennies in our national debt.

While these figures at the top of Fig. 19*A* are increasing, there are other figures, at the lower side of the chart, that are decreasing. At point *E*, notice that a frequency of 300,000,000 cycles is on a line with a 1-meter wavelength.

19-3. Frequency and Wavelength.—When you watch waves of water move past the end of a pier, the waves may be 10 ft apart (from one tip or crest to the next crest); if one wave passes during each second of time, you know that the waves are traveling 10 ft per second. This wave movement is a kind of vibration in the water; the wavelength of this vibration is 10 ft, while its frequency is 1 per second. If now the wind changes so that the waves are only 5 ft apart (but traveling at the same speed of 10 ft per second), twice as many waves must pass during each second. The wavelength is now 5 ft, the frequency is 2 per second. As the wavelength decreases, the frequency increases (as long as the speed is unchanged).

Similarly, a sound travels through the air at, roughly, 1000 ft per second. If this sound is a low note that vibrates 100 times per second, then 100 waves (or air-pressure crests) pass your ear each second. As these waves radiates or move in a straight line through the air, the distance between them must be 10 ft. (Wave-length = 10 ft. Frequency = 100 per second.) If the sound changes to a higher note, of 1000 vibrations per second, it still travels at the same speed of 1000 ft per minute; however, the wavelength (or distance between air-pressure crests) is now only 1 ft.

For any other part of Fig. 19*A* except "sound," the speed at which the electromagnetic radiations travel is the speed of light or the speed of electricity. This speed is about 186,000 miles each second; this is also 300,000,000 meters per second (for each

* In the figure 10^{15}, the ^{15} shows the number of zeros in the whole number. 10^{15} is the same as 1,000,000,000,000,000. Similarly

$$10^6 = 1 \text{ million} = 1{,}000{,}000.$$
$$10^{10} = \text{ten billion} = 10{,}000{,}000{,}000.$$

meter is about 40 inches long). At point E, where a radio beam changes at the rate of 300,000,000 cycles per second, the distance between crests of these radio waves is 1 meter. Moving one scale division to the left of E, to where the frequency is decreased to 30,000,000 cycles or 30 Mc, the wavelength* is increased to 10 meters.

At the lower frequencies (to the left of D, the broadcasting range in Fig. 19*A*), the wavelength is seldom mentioned; however, to the right of E, we hear of radar or other units using "centimeter waves"; a 3000 Mc signal has 10-cm waves. Farther to the right, heat and light wavelengths are often described in millimicrons or in angstrom units, as explained later.[19-8]

19-4. Sound.—Most a-c motors or transformers have a humming noise, a low note such as a man might hum. Operating from 60-cycle supply, this hum is a vibration of 120 cycles per second.† As shown in Fig. 19*A*, the range of most sounds is between 20 and 10,000 cycles; there are air vibrations below 20 or above 20,000, but the ear‡ cannot respond to them. To know this range of sound frequencies, notice that middle C on a piano is at a frequency of 256 cycles; one octave higher is 512 cycles. Raising the note or pitch by one octave doubles the frequency. If you can whistle through a range of two octaves, your top note is a vibration four times the frequency of your lowest note.

While the highest main note of a piano is about 4000 cycles and that of a violin is 3000, most musical sounds contain overtones or frequencies above 4000; these higher frequencies make a piano note sound different from a flute or a violin note. If these frequencies above 4000 cps are not included in a recording or a broadcast, the result does not sound the same as the instrument itself. Therefore a range of 6000 cycles is needed for each "channel" through which radio entertainment is sent.

* The radio wavelength (in meters) is always equal to 300,000/kilocycles. So, a station broadcasting at 1000 kc has a wavelength of 300 M. A "short-wave" radio station, using a 5-M wave, has a frequency of 60,000 kc.

† The transformer hum is caused by changes of a-c power within the iron core; this power changes once during each half cycle of current flow, so the sound has a frequency twice that of the a-c supply.

‡ The human ear responds best to sounds at about 1000 cycles, with less response to higher or lower frequencies. Only a young ear hears well above 10,000 cps.

In industry, noise meters may measure the quantity of noise produced at any spot; they may also locate the frequencies of the main sounds produced by a machine, to help tell which gear or other part is noisy. Such noise meters use electronic circuits; the noise is changed into an electric vibration or signal by a microphone. Since sounds below 1000 cps affect the human ear less than higher frequencies, the meter includes circuits that allow for this.

19-5. Supersonics.—As a sound rises to very high pitch (10,000 to 20,000 cps) it is very shrill; gradually it fades and cannot be heard. The vibration is still there, but it is above the range of the ear; it is now a supersonic (above sound) vibration. Some insects and animals produce or hear such "noises," which man never hears. One type of police whistle is heard by a dog far away, but cannot be heard by a man near or far. A bat flies in the dark without striking a wall or even a wire inside a room; the bat makes a supersonic "noise," at about 50,000 cps, and then listens for the echo reflected from the wall or the wire. If the bat's mouth or ears are covered, it strikes the wall. Making more than 20 of these "noises" each second, the bat acts like a radar (whose electronic circuit sends out pulses of high-frequency waves, then measures the time of their reflected return).

In industry, supersonic vibrations (produced by electronic circuits and vibrating crystals) may mix together liquids that usually stay apart. Such waves also measure distances through water or locate defects in thick metal castings. These results come from the waves vibrating at high frequency; electron-tube oscillators produce the waves, while other tube-operated circuits measure the time before the reflected waves return.

These supersonic waves are like sound, moving through air, water or metal at speeds less than 1 mile per second. Their frequencies are the same as those used for some kinds of radio; however, at this same frequency, the radio waves are electromagnetic, and travel 186,000 times faster through space.

19-6. Radio.—So much is written about radio, discussion of it here is needless, except for a few names. Radio equipment uses mostly circuits of vacuum-tube oscillators (see Chap. 20) to produce and to receive high-frequency signals. Figure 19*A* shows how radio services use the frequency range above 10 kc, to wavelengths of 1 cm or less. This range is split into the seven

divisions marked with letters for "Very Low Frequency," "Low Frequency," "Medium Freq." "High F," "Very-High F," "Ultra-High F" and "Super-High F." The entire "Broadcasting Range" (550 to 1700 kc) for most home entertainment is at *D* in the "Medium Frequency" division; here dozens of separate programs are sent at the same time, one of which is selected by turning a dial (to tune the receiver to the frequency of the station desired). "Shortwave" broadcasts occur in the HF and VHF divisions; future broadcasting of radio and television will make greater use of these divisions. War activity makes great use of the VHF and SHF divisions,* which were almost unused 10 years ago.

Since a radio program consists of sound, the information or signal broadcast through space must include sound frequencies. Such sound (at less than 6000 cps) is carried along on a radio wave that vibrates at least 100 times as fast. The radio wave is merely the carrier; by itself, it produces no sound at the radio receiver, for its radio frequency (rf) is far above the human-ear range. However, the program is carried by changing the shape of the rf waves at a slower rate [called the *audio frequency* (af), 50 to 6000 times per second]; this "slow," or af, change operates the receiver speaker—the rf wave merely carries the af signal there.

When the audio signal is loaded onto the rf carrier wave, we say that the carrier is modulated by the signal; the radio oscillators may be controlled in different ways to produce this modulation. If the sound signal affects the rf wave so as to change the size or strength of this carrier wave (but does not change the radio frequency), this is the standard method used for many years and is called *amplitude modulation* (AM). However, if the size of rf wave is kept unchanged, but the sound signal makes the frequency of the rf wave change so as to carry the program, this is called *frequency modulation* (FM). Using FM requires not only a different form of transmitter circuit (still using oscillators) but it also requires different receiver circuits. Future FM broadcasts will use frequencies in the VHF division; many more program

* These centimeter waves, like light waves, can be focused into narrow beams; in contrast, radio waves near the broadcasting range spread in all directions, so that their direction is not easily controlled. Notice how the shortest radio waves are closer (in the spectrum) to light waves; they behave quite like beams of light, traveling in straight lines and permitting radio "shadows."

channels (each 6000 to 200,000 cycles wide) can be used here than in the present crowded broadcasting range.

19-7. Induction or Dielectric Heating.—Frequencies in these same ranges (as used by sound, supersonics and radio) are used also in the industrial field of electrical heating. (This does not apply to resistance-type electric furnaces.) Even at 60 cycles, the iron of a motor or a transformer is heated by the small currents flowing in the iron, caused by the frequent reversal of the current.

At 360 or 960 cycles, this "hi-cycle" a.c. causes greater heating in iron or other magnetic materials. Metal parts of automobile bodies are painted and then passed through an "oven," which has an open coil (6 ft across, perhaps 15 ft long) through which the a.c. flows. As the metal parts enter this 360-cycle coil, heat is quickly produced inside the metal, thereby drying the paint from the inside out. Meanwhile, the air in the "oven" is not much warmer than outside; the metal "sings" with a 720-cycle note.

Many plants use motor-generator sets to produce a.c. at 3000 cycles, which is fed to small induction furnaces. Here blocks of metal (sometimes copper or brass, 3 inches across by 10 inches long) are made red hot in only 30 or 40 seconds. This heat is produced inside the metal block because of the high-frequency currents produced or induced in the block by the near-by a-c windings of the oven. Notice that the a-c winding does not need to touch the metal block, but merely to be around it. This kind of heating is caused by the high-frequency current, no matter how this a.c. is made. Above 15,000 cycles (which is about the upper limit for motor-generator sets) higher frequencies are produced by electric spark-gap equipment, to perhaps 200,000 cycles. This frequency is far inside the radio range shown in Fig. 19*A*, yet no electron tubes need be used so far for this induction heating of metals. The high-frequency current is used inside the furnace, which is shielded so that it cannot cause radio waves to pass into space.

However, further heating comes from using frequencies much higher than 15,000 or 200,000 cycles. Chapter 20 describes an oscillator circuit used in an electronic heater, to furnish a.c. at 530 kc. This high-frequency current passes through a heavy wire around the piece of metal to be heated; it induces similar currents inside the metal piece, quickly heating it. Frequencies

up to 2 or 3 megacycles are used for such metal heating; the higher frequencies cause special results, so that only certain edges of the pieces are heated. All these heating results are caused by the high-frequency a.c. Electronics merely provides a better way of getting this needed power supply.

At still higher frequencies (5 to 50 megacycles) electronic oscillators are used to heat materials that are not metal.[20-18] This heat is caused by a different action inside the material, so this is called *dielectric heating.* However, the electronic circuit is still an oscillator designed to furnish this very-high-frequency power supply.

A similar oscillator (called an *Inductotherm*) produces VHF waves for heating the human body; it produces artificial fever, when desired for medical treatment. The heat is produced inside the blood vessels, when VHF electricity flows in wires several inches away from the body.

19-8. Light and Color.—Near the center of Fig. 19*A* is the band of frequencies that can be seen by the human eye; this visible radiation is called *light.* The frequency of light is a thousand times greater than the highest radio frequency now used; a light wave is shorter than one-millionth of a meter, so there are about 50,000 light waves to the inch.

Each color of light has a different wavelength, or frequency; in Fig. 19*A*, notice that red has a lower frequency than violet, or that violet has a shorter wavelength than red. The colors of the rainbow (red, orange, yellow, green, blue, violet) are named in order as the wavelength decreases.

When charts are used to show colors (or heat) by wavelength, often the wavelength increases from left to right; the example in Fig. 19*B* shows red toward the right, violet toward the left. (Later Fig. 19*B* will be used to help choose a phototube for use with colors.) Now let us see what kind of wavelength is shown at the bottom of the chart; notice the figure 4000, above violet, and 7000, near red. These numbers are angstrom units, shown as 7000 Å, or 7000 AU.

At *H* in Fig. 19*A*, a line is marked 10^{-10} M. = 1 angstrom*. This

* In the figure 10^{-10}, the ^{10} shows the number of zeros in the whole number, but the $^{(-)}$ means that these zeros are below the line in a fraction. So, 10^{-10} is the same as 1/10,000,000,000. Similarly, $3 \times 10^{-6} = 3/1{,}000{,}000$ or three millionth

shows that 1 AU is a ten-billionth of a meter; 10,000 AU is 10^{-6} M or a millionth of a meter. Another name for a millionth of a meter is a micron (μ), as shown at G (near the visible range of Fig. 19A). Wavelengths of light may be given in angstrom units, or in millimicrons. In Fig. 19B, the vertical line marked 4000 AU (violet) is also marked 400 millimicrons.*

In Fig. 19B we see that a violet-colored light may have wavelengths between 3800 and 4300 AU; a green-light wavelength is longer, or between 4900 and 5600 AU. Notice the curve marked "Human eye response"; the shape of this curve shows that a

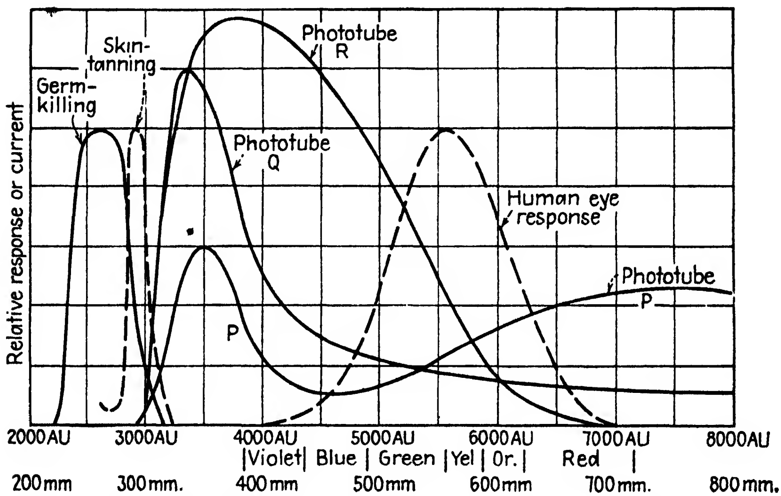

FIG. 19B.— Phototube and eye response to color wavelengths.

human eye usually responds best to a green or a yellow light. If a blue light, a yellow light and a red light are adjusted so that each sends the same amount (radiant energy) of light over the same distance to the eye, the yellow light looks much brighter than the other two. Also, just as there are "sounds" of too-high frequency to be heard by the human ear, so there are "colors" of too-high or too-low wavelength to be seen by the human eye. The average eye cannot see or respond to wavelengths below 4000 AU or above 7000 AU (therefore, the "visible range" is also 400 to 700 millimicrons). As supersonic vibrations can be heard by a

* Since a millimicron is the name for $\frac{1}{1000}$ micron, 400 millimicrons = 0.4 micron = 4000 AU.

dog or a bat, color wavelengths beyond the human-eye range can be "seen" by some kinds of "electric eye," or phototube. When a person is colorblind, he may not be able to see a red color; to him there is no light of this color for it looks black. Notice that his eye fails to respond to a wavelength of 6500 AU, in the same way that most eyes cannot respond to 7500 or 8000 AU.

When light rays of all wavelengths between 4000 and 7500 AU are mixed together in the right amounts, the result is white light. Outdoor daylight is called *white* light because it usually contains all the colors; near sunset this may not be true.

19-9. Infrared, or Heat, Rays.—Years ago when men learned that heat rays were like light rays, except that they were longer in wavelength, they did not know about X rays, or other rays shown near the right-hand end of Fig. 19*A*. To them, the low frequencies of sound were well known; from this starting point, light rays seemed far out in the spectrum. When the rays produced by a hot (but not red-hot or white-hot) metal were found to have wavelengths longer than the visible red rays, so that their place in the spectrum was between those of light and sound, it was natural that these heat rays should be called *infrared* rays (meaning "inside" or "nearer than" the red rays). Similarly, when they found other rays shorter than the visible violet rays, which therefore were placed beyond the violet on the spectrum, these new rays were called *ultraviolet* (meaning "beyond" or "farther than" the violet rays). These two names are still used.

Anything that is hot enough to be seen in a dark room, is giving out rays of visible light; at the same time, it is also giving out much greater amounts of heat rays, which cannot be seen but which can be felt and measured; these invisible rays are infrared rays and have wavelengths from 7500 AU to 100,000 AU and higher. To show infrared or heat wavelengths, a chart may use microns instead of angstroms, as in Fig. 19*C*. This chart shows how an object (such as a piece of metal, black when cold) produces more rays of shorter wavelength as its temperature rises. The lowest curve of Fig. 19*C*, showing the radiation produced when the metal or "black body" has a temperature of 1000 degrees K,*

* The temperature in degrees Kelvin is equal to degrees Centigrade + 273°. The zero of the Kelvin scale is at absolute zero, or −273°C. Temperatures like 2000 K or 4000 K are used when speaking of objects that are so hot that they produce visible light; the color of that light is called the *color*

has its peak or highest value at a wavelength of 3 microns. When the temperature rises to 1500 K, there is much greater total radiation (shown by the area or space under the curve), and the peak is now at 2 microns.

Notice how the 1000-K curve reaches to the left, into the region of visible rays; the curve is above the zero line in the red and yellow portion, but not beyond. This shows why a piece of metal at this temperature has an orange color. (At 800 K, the curve barely reaches the red region, and the color temperature is a dull

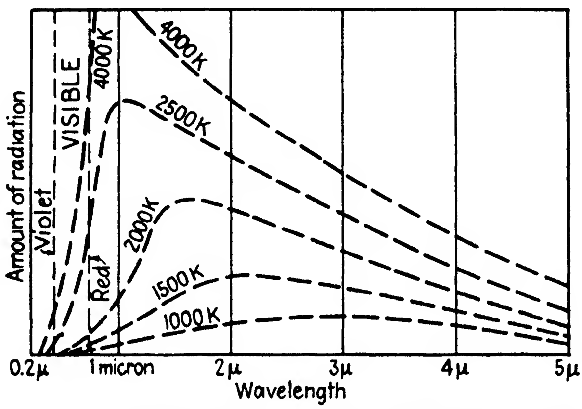

FIG. 19C.– Radiation from an object at high temperatures.

red.) Although some of its radiation can be seen, nearly all its rays are infrared and at wavelengths greater than 1 micron. Even at 2500 K, where the curve is above zero all through the visible range, these visible rays are yet a small part of the total radiant energy. Such a temperature (2500 K) is above the melting point of most metals; the tungsten filament enclosed in an electric-lamp bulb may operate at this temperature, giving a yellow-white light. If objects can be heated to 3000 K or 4000 K, they produce bright white light; this 4000-K curve in Fig. 19C includes plenty of rays at all visible wavelengths, which combine to make white light. To produce light that matches the color of

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temperature. The tungsten filament of an electric lamp works at 2500 K to 2800 K.

Also, 1000 K = 1340°F; 2000 K = 3140°F; 3000 K = 4940°F. A rise of 10 degrees K is a rise of 18°F.

sunlight or blue sky, an object would have to be heated to 6000 or 7000 K.

19-10. Ultraviolet Rays.—Of those wavelengths close beyond the visible violet, the most useful region is between 2000 and 4000 AU, shown in Fig. 19*B*. The sunlight we receive outdoors includes wavelengths to 2800 AU, as well as the visible and infrared regions. (However, most of this ultraviolet sunlight cannot pass through window glass.) The invisible wavelengths near 2900 AU cause the burning and tanning of the skin, whether this light comes from the sun or from a lamp.

Most of the lamps that produce large amounts of ultraviolet rays are electronic; electrons flowing through mercury vapor produces such rays. When the outside of the lamp is made of special glass or quartz, these rays may pass through into the outside air. Some of these mercury lamps give out rays close to 2500 AU, which can kill germs These germicidal lamps are electronic; electrons must stream through the mercury vapor to produce these rays. The human body can safely be exposed to such rays only under a doctor's care

Fluorescent lamps are electronic; streams of electrons pass from one end of the lamp to the other end,* through mercury vapor. This action produces ultraviolet rays (at 2857 AU), which cannot be seen and which cannot pass through the glass wall of the tube. However, when these invisible rays strike against special materials painted on the inside of the tube wall, the materials fluoresce; that is, they glow brightly and give large amounts of visible light; this light passes easily through the glass walls, to be used outside. Notice that the ultraviolet energy changes into energy of longer wavelength, which is visible When different materials are painted on the inside of the tube, different colors of light are produced, using the same supply of ultra violet rays.

19-11. Color Response of Phototubes.—The human eye receives a different color sensation from green light than it receives from red light. However, lights of different colors reaching a phototube make its cathode produce different amounts of electrons. The phototube current is a measure of the total

* Since both ends of the fluorescent tube are heated the same amount, electrons may flow both ways through a tube operated on a-c supply; such tubes do not rectify.

light it receives, of all colors; the phototube does not form an image such as the human eye forms. If a fly crawls up a white wall within view of the phototube, the phototube cannot "tell" that the fly is there unless the fly occupies perhaps one-twentieth of the total space viewed by the phototube. The dark fly then causes a decrease in phototube current; this current does not change as the fly moves about within the space viewed.

The ability to sort or detect different colors depends on the kind of phototube used, regardless of the circuit in which it works. From the light-sensitive metal surface of the phototube cathode, more electrons are driven by one color of light than by some other color of light. In Fig. 19*B*, the curve *P* shows the amount of current produced by various colors of light reaching one kind of phototube (GL868/PJ-23, general-purpose, gas-filled type). This phototube responds to all colors of visible light and to many invisible rays. Its large response between 7000 and 10,000 AU lets it work well with hot-filament lamps (like auto headlights) or with daylight. These infrared rays may be invisible to the human eye, yet they are easily changed into a useful signal by this phototube.

This tube (curve *P*, Fig. 19*B*) has similar response to either violet light or green light; it cannot sort or distinguish between these two colors. However, if we place in front of the phototube a light filter or colored glass that passes green light but does not pass violet light, then this combination of light filter and phototube passes more current in response to a green light than to a violet light; a green box may energize the relay, while a violet box does not. Of course, when a different kind of phototube is used (such as curve *Q* in Fig. 19*B*), the phototube itself passes more current responding to violet light than to green light; here a color filter may not be needed.

Using curve *P*, can this phototube alone sort a red box from a white box, in daylight? This curve is high in the red region (above 6000 AU); also, the large area under the curve through all the colors (4000 to 7000 AU which combine to make white light) shows that this phototube has large response to white light. This phototube may pass about the same current for either a red box or a white box. However, if a colored-glass filter prevents red and infrared rays from reaching the phototube (while letting other colors pass through), the phototube receives a large amount of

light from a white box, but very little from the red box, so now it can select between them. Notice also that another phototube (curve *R* in Fig. 19*B*) by itself responds well to white and colors between 4000 and 6000 AU, but cannot "see" red.

19-12. X Rays and Gamma Rays.—Near the right-hand end of Fig. 19*A*, gamma rays are shown having wavelengths less than 1 AU. These rays come from radium,* the rare metal discovered by the Curies. We know that these rays can pass through the human body and are used in medical treatment. Even tiny pieces of radium are so powerful that they are dangerous; their cost is high.

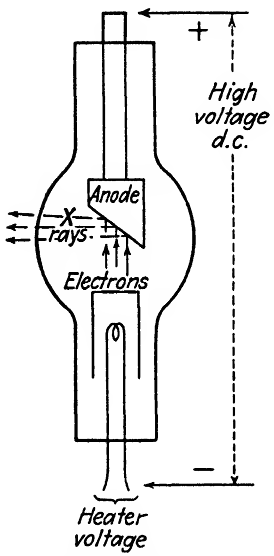


FIG. 19*D*.—Working parts of an X-ray tube.

Since radium was discovered, it has been found that similar rays are produced by high-vacuum tubes that operate at very high voltages. These rays are not so short as gamma rays; they would appear in Fig. 19*A* at wavelengths between 100 and 10 AU (between the ultraviolet and gamma rays). Special electron tubes are made to produce these X rays; as shown in Fig. 19*D*, such a tube has a hot-filament cathode and an anode made of very heavy metal. Electrons flow from the cathode to the anode as in any diode tube. However, a large d-c voltage is used between cathode and anode of the X-ray tube; the anode is so positive that the electrons rush to it at very high speed. The electrons strike the metal anode with such speed that new rays are made; from the slanting surface of the anode these X rays seem to bounce sideways and out through the wall of the tube. As the d-c voltage (anode-to-cathode of the X-ray tube) is increased, the wavelength of the X rays decreases. Some tubes now operate at more than a million volts; the X rays produced have wavelengths less than 1 AU, and give results equal to the gamma rays from radium.

* Radium continually gives off three kinds of rays, named alpha, beta and gamma (the A, B and C of the Greek alphabet); of these, only the C rays (gamma rays) are electromagnetic.

Such high-voltage X rays serve industry by helping to photograph thick metal objects; the very short wavelength of these rays also lets them pass between the tiny crystal particles of various metals, making a diffraction picture, which helps to analyze the conditions inside the metal.

The cosmic rays (shorter than gamma or X rays) play no part in industrial electronics; they seem to come from space outside the earth. Cosmic rays merely complete the chart of known electromagnetic radiations.

Questions

1. Which of these can be seen by the average human eye?

(a) 1 angstrom	(b) 10^{-15} cycles
(c) One billion megacycles	(d) 500 millimicrons
(e) 2500 K	(f) 2857 AU
(g) 600 microns	(h) 8000 AU
(i) Half of a millionth of a meter.	

True or false? Explain why.

2. All ultraviolet rays kill germs.

3. A fluorescent lamp at 3500 K feels warmer than a tungsten lamp at 2800 K.

4. Frequencies of 400, 600 and 800 cps may be carried on one radio frequency at the same time.

5. Rays of 1 M or 1 AU wavelength pass through glass more easily than rays of 1000 AU.

6. A phototube that "sees" very short wavelengths can operate a relay faster than a phototube that "sees" only longer wavelengths.

7. All waves at 25 kc are supersonic.

8. A beam of light may be modulated at sound frequency.

9. Phototube *R* (Fig. 19*B*) is well suited to respond to the light of a hot-filament lamp.

10. Blinking light signals from ship to ship use modulated light beams.

11. If the filament of an X-ray tube is made hotter, the X rays have shorter wavelength.

12. A lamp used for infrared heating has a hotter filament than a lamp for lighting.

13. All oscillations at 1000 cps are sound vibrations.

CHAPTER 20

INVERTERS, OSCILLATORS AND THE ELECTRONIC HEATER

Inverters and oscillators produce a.c., or alternating voltages, usually from a d-c supply; this action is the reverse of the action of a rectifier. Units that change a.c. into d.c. are called *converters* or *rectifiers;* all units that change d.c. into a.c. are *inverters.* In electronics, the name "inverter" means a unit that uses vapor-filled tubes; therefore, it may produce large voltage signals or alternating-current output at low frequency (such as 60 or 1000 cycles); an oscillator uses high-vacuum tubes, so it may produce a.c. at higher frequency.

Dozens of oscillator circuits are described in textbooks. Here we discuss a few basic circuits, to see how an inverter and an oscillator work; their use in industry is of interest.

20-1. A Single-tube Inverter.—Thyratron tubes like those studied in earlier chapters may be used in inverters.* Since these vapor-filled tubes here receive power from a d-c supply, inverter circuits must use special methods to "turn off" these tubes, for the tube grids cannot do so.

An inverter using only one tube is shown in Fig. 20*A*. When switch *S* is closed, this circuit receives d-c power;† it produces a changing output voltage having a waveshape shown between points 7 and 4. (Such voltage changes are used to fire another thyratron in one type of seam-welder control.) Before *S* closes, notice that capacitor 1*C* has no charge (for it drains through 1*R*, 2*R*, 3*R* and 4*R*). When *S* closes, the tube-1 grid stays at a low potential on the voltage divider (1*R* and 2*R*); for an instant the cathode 4 is at the same potential as point 7 (since there is no voltage across *C*). Electrons now charge capacitor *C*, flowing from 2 through 3*R* and 4*R*, so that the voltage across *C* increases.

* Thyratrons with shorter deionization time[11-3] let the inverter work at higher output frequency.

† The tube filament is heated by d.c. (using a series resistance) or from some a-c supply.

This lowers the potential of cathode 4 so that, at point A in Fig. 20B, it nearly reaches the grid potential, so tube 1 fires. The electron flow that had been charging C now passes through tube 1 and inductance T; capacitor C discharges, forcing a large electron flow from 4 through tube 1 and T to point 7. This tube-1 current increases slowly (at B in Fig. 20B) because the inductance T prevents a sudden change of current. The entire C voltage (except for 15 volts' arc drop across tube 1) is making the current in T increase and is storing energy in T. At D the capacitor has discharged. However, the current in T must continue to flow; the energy stored in T produces whatever voltage is needed to drive the tube-1 anode positive at E, to let electrons continue

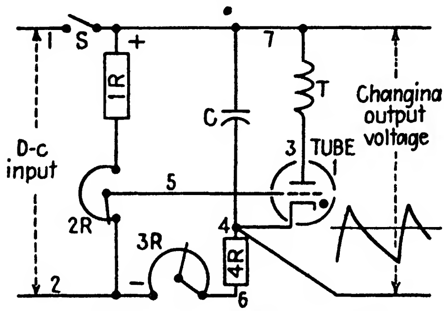


FIG. 20A.—Single-tube inverter.

to flow from point 7 into C, then cathode to anode of tube 1, to point 3. This flow charges C until all the T energy has been used; the tube-1 anode current stops, leaving C charged to the voltage F. The anode potential instantly returns to point 7, while cathode 4 is still at G. Electrons again flow from 2 through 3R and 4R to charge C.*

As long as cathode 4 is more positive than anode 3 and point 7, the d-c input voltage cannot force current through tube 1. In the short time H (Fig. 20B) before cathode 4 again becomes more than 15 volts below (more negative than) anode 3, all the gas particles in the tube must have lost their charges (deionizing the gas), or tube 1 again passes current.† If H is longer than the

* This electron flow first removes that charge in C that kept 4 more positive than 7; further flow then charges C so that 7 becomes more positive than 4.

† Inductance T makes it possible to turn off tube 1. If this inductance is not used, there is no stored energy which can reverse the capacitor voltage

deionization time[11-13] of the tube, the grid regains control; tube 1 is not fired again until C has received enough charge so that cathode 4 again approaches grid-5 potential, at I.

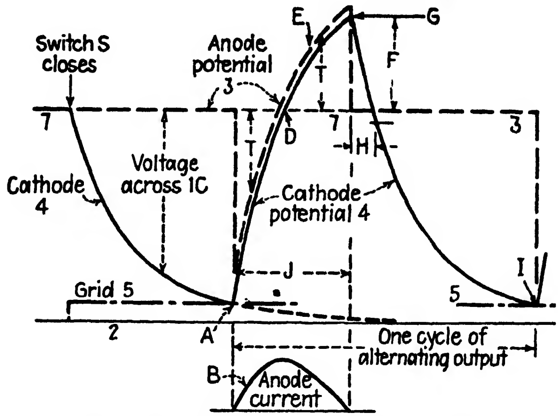


FIG. 20B.—Waveshapes in inverter circuit of Fig. 20A.

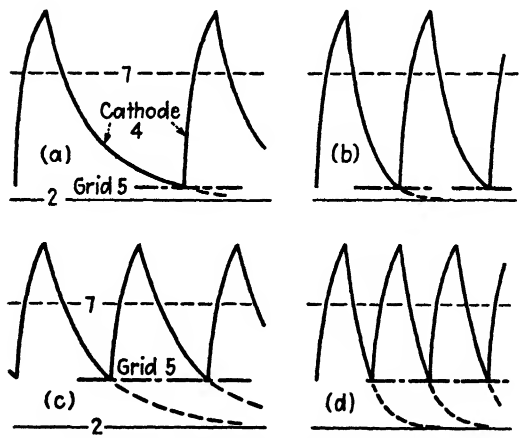


FIG. 20C.—Changes of inverter frequency.

Figure 20B shows many things happening during the short time J while tube 1 passes current. Keeping J constant, the over-all length of each wave of output voltage may be changed by turning either 2R or 3R in Fig. 20A. Leaving 2R set so that slider 5 is near to point 2, the upper parts of Fig. 20C show the

to make cathode 4 become more positive than anode 3; tube 1 cannot be turned off long enough to let its grid regain control.

output wave (*a*) when $3R$ is turned clockwise so most of its resistance is in circuit, thereby decreasing the rate at which capacitor C charges, and (*b*) when $3R$ has less resistance, so C charges faster and fires tube 1 sooner. For these two positions of $3R$, parts (*c*) and (*d*) of Fig. 20*C* show how tube 1 is fired sooner when $2R$ is turned clockwise, raising the grid potential. In (*d*) tube 1 fires many more times per second and the output wave* has higher frequency.

Because of the waveshape, the single-tube inverter may be used as a saw-tooth oscillator. In the oscillograph circuit of Fig. 27*E*, thyratron tube 5 acts as such an inverter.

20-2. A Two-tube Inverter.—While two tubes may be connected in many ways to operate as an inverter, Fig. 20*D* shows a parallel-inverter circuit (so named because the direct current divides; the current through one tube never passes through the other tube also). This is a separately excited inverter, for an a-c signal voltage must be applied† to the grids of tubes 1 and 2 to control the time at which each tube fires.

Figure 20*D* looks like a rectifier circuit.‡ However, while the anode transformer $2T$ and the tubes are connected as in a rectifier, there is no a-c voltage at terminals 3 and 4 unless tubes 1 and 2 make it appear there by inverter action. This can be done if we can make tubes 1 and 2 fire in turn. From the d-c input, electrons flow from point 2 through tube 1 and pass left to right to the midtap 7 of transformer $2T$; if this flow then stops, and electrons pass instead through tube 2 and right to left through $2T$ to reach the midtap, we see that this flow in $2T$ changes direction. These changes and reversals of current in $2T$, caused by alternate firing of tubes 1 and 2, produce an alternating voltage in the $2T$ secondary winding, appearing at terminals 3 and 4.

* Instead of using this output wave (between points 7 and 4), a transformer may be used in place of T; the output voltage is then taken from the secondary winding of this transformer, and is caused by the changes in primary current shown in Fig. 20*B*.

† A building may have a large d-c power supply but only a small amount of a.c.; this a.c. can supply a signal to the tubes so that the inverter produces alternating voltage. This output voltage will not have sine waveshape except under special conditions.

‡ Notice that the tube cathodes connect to the (−) side of the d-c input, while the cathodes of a rectifier connect to the (+) side of the d-c load. Often a rectifier circuit will invert (pump back into the a-c supply) if the terminals of a d-c motor load are reversed.[24-13]

But recall that, when a vapor-filled tube is passing current from a d-c supply, its grid cannot regain control to shut it off unless another device is added, such as capacitor C in Fig. 20D. Without C, tubes 1 and 2 both may pass direct current at the same time, after the first turn-on signal at their grids; such anode currents, flowing steadily through 2T, produce no voltage at terminals 3 and 4.

Suppose that the tubes have been heated (perhaps from the same a-c supply that provides the grid-signal voltage). When S closes, neither tube fires until its a-c grid voltage becomes positive. Since grid transformer 3T drives one grid negative while the other grid is becoming positive, only one tube fires, say, tube

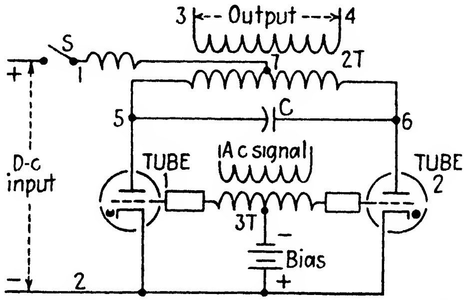


FIG. 20D.—Two-tube inverter, separately excited.

1. As electrons flow from 2 through tube 1 and 2T, the voltage across tube 1 drops to 15 volts, and voltage 5-to-7 increases; this changing voltage across one half of 2T primary makes a similar voltage appear in the other half 7-to-6, so that point 6 becomes much more positive than 5. Capacitor C is charged by this 6-to-5 voltage.

During the next half cycle of the signal voltage, the a-c grid voltage reverses and fires tube 2; at the same time tube-1 grid becomes negative, but this cannot turn off tube 1. Electrons now flow from 2 through tube 2 and 6-to-7 of 2T. The voltage across tube 2 also drops to 15 volts, causing the potential at point 6 to drop a large amount. However, when the 6 side of capacitor C drops in potential, the 5 side must also drop (since voltage across C cannot change instantly). Since point 5 is already only 15 volts more positive than point 2, capacitor C forces point 5 (anode of tube 1) far below (more negative than) cathode 2, so anode current stops in tube 1. Capacitor C now changes its charge;

electrons flow from 2, through tube 2 and into C. By the time that anode 5 again rises 15 volts above cathode 2, the tube-1 grid has regained control so that it prevents tube 1 from firing. Point 5 now rises to its most positive potential, while 6 remains within 15 volts of point 2. Capacitor C becomes charged to this voltage difference: (+) at 5, (−) at 6.

When the a-c grid-voltage signal again fires tube 1, point 5 again drops close to point 2; the charge on C now drives the tube-2 anode more negative than its cathode 2, so that the tube-2 current stops. C acts as a *commutating* capacitor, to turn off one tube when the other tube fires.

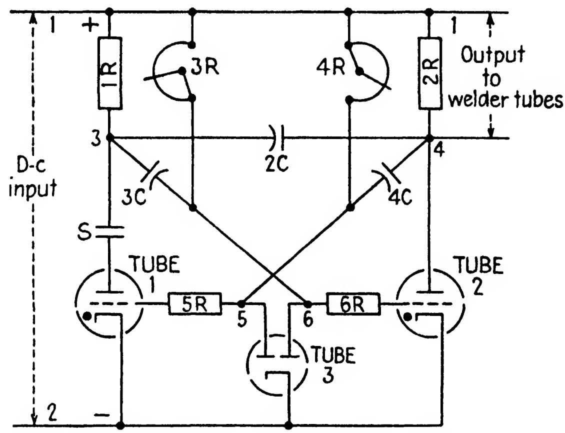


FIG. 20E.—Two-tube inverter, self-excited for adjustable frequency.

20-3. A Self-excited Inverter.—While the circuit of Fig. 20D needs an a-c signal voltage to fire the tubes at the desired frequency, Fig. 20E shows a parallel type of inverter which can control the frequency of its output voltage. Instead of producing an a-c output from a transformer, this circuit uses the changes of potential at point 4, to control other thyratrons in a seam-welder panel.* When tube 2 is firing, point 4 is at low potential and prevents the welder tubes from firing; when tube 2 is not firing, point 4 is at high potential and lets the welder tubes fire.

While the starting contact S is open (above tube 1 in Fig. 20E), point 3 is at the same potential as point 1. The tube-2 grid (at

* Parts of this inverter circuit are not shown, such as peaking transformers that fire tubes 1 and 2 in step with the a-c welder voltage. The complete circuit is shown in the footnote reference, p. 118.

point 6) is positive. (Without tube 3, point 6 would be at some potential between points 1 and 2, depending on the resistances of $3R$ and $6R$ as a voltage divider; tube 3 acts as a switch that prevents points 5 and 6 from rising much above point 2.) Tube 2 is firing, so point 4 is only 15 volts more positive than point 2. Capacitor $2C$ (like C in Fig. 20D) has a large voltage charge—(+) at 3, (−) at 4. Capacitor $3C$ also has large voltage—(+) at 3, (−) at 6. But $4C$ has almost no charge (for points 4 and 5 are both about 15 volts above point 2).

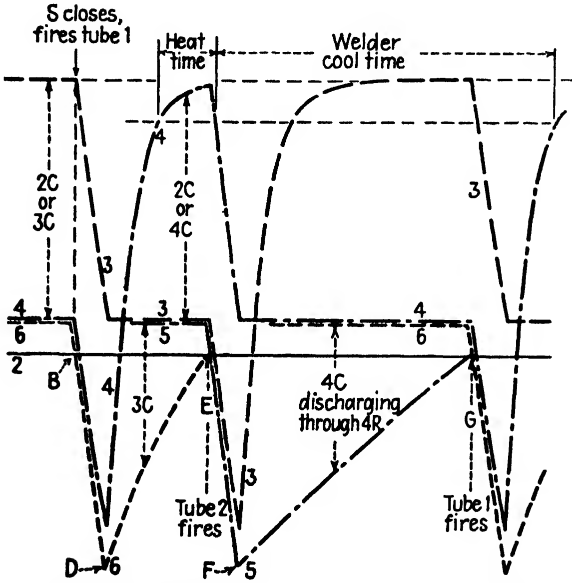


FIG. 20F.—Waveshapes in inverter circuit of Fig. 20E.

Closing the starting switch fires tube 1. As the point-3 potential drops, capacitor $2C$ drives anode 4 negative, stopping the tube-2 current as in Sec. 20-2. At the same time, capacitor $3C$ drives grid 6 negative, to point D in Fig. 20F; when 6 drops below 2 (at B), current stops in this half of tube 3. As long as 6 is negative, tube 2 does not fire again. Capacitor $2C$ recharges quickly until 4 is much more positive than 3; capacitor $4C$ also charges to about this same voltage. However, grid 6 rises more slowly, as capacitor $3C$ loses its charge through resistor $3R$. At E, grid 6 reaches cathode 2, firing tube 2 again. This time, as the potential of point 4 drops, capacitor $2C$ forces anode 3 nega-

tive, stopping the current flow in tube 1. Also, capacitor $4C$ forces grid 5 very negative, at F; $4C$ must discharge through resistor $4R$ to let grid 5 rise high enough to fire tube 1 again, at G. By turning $4R$ (clockwise, decreasing its resistance), capacitor $4C$ discharges more quickly, to fire tube 1 sooner and shorten the welder "cool time." Likewise, $3R$ is turned clockwise to shorten the "heat time." If one or both of these times is shortened, the inverter operates more often, at increased output frequency.

A circuit similar to Fig. 20*E* is used in Fig. 27*F*, but the thyratrons are replaced by two high-vacuum triodes in tube 2. Such a circuit is sometimes described as a "multivibrator."

20-4. Oscillators.—High-vacuum amplifier tubes like those studied in earlier chapters may also be used in oscillator circuits. Some types of radio receiver include an oscillator. An oscillator circuit is self-contained; taking power from d-c or low-frequency a-c supply, the oscillator produces a-c output at a higher frequency, which depends on the sizes of capacitors and inductances used in the oscillator circuit. However, if something outside the oscillator causes a change in the oscillator-circuit capacity or inductance (as when a metal vane passes between the coils in an oscillator circuit), the output frequency of the oscillator changes —the oscillator may stop working.

In industry, oscillators have two main uses. First, an oscillator may be an off-on device; a very tiny outside signal or changed condition may stop the oscillator action and thereby operate a relay or a visible signal. In this case, the frequency of the oscillator is not important as long as it is easily stopped by the outside signal.

In the second use, the oscillator supplies its high-frequency output to produce action that cannot happen at lower frequencies. The radio oscillator produces high-frequency waves that travel through space carrying news or music. The "fever-machine" oscillator makes waves of the right frequency to produce heat in the blood of a person. As an example of an oscillator used in this way, let us study the circuit of an electronic heater used for the rapid heating of metals in industry.

20-5. The Electronic Heater.—As is mentioned in Sec. 19-7, metal parts are quickly heated when they are near a cable carrying electricity at high frequency. The electronic heater shown

in Fig. 20G is a vacuum-tube oscillator that produces large power output (such as 5, 15 or 50 kw) at about 530,000 cycles per second, for heating metal parts in this way. It operates from the 60-cycle power supply.

The high-frequency power output of the electronic-heater cabinet is fed by a pair of external leads to a load coil of several turns, fitted closely around the piece to be heated. The turns of this coil act as the primary of a transformer, while the workpiece of metal is the secondary of this transformer. Current from the

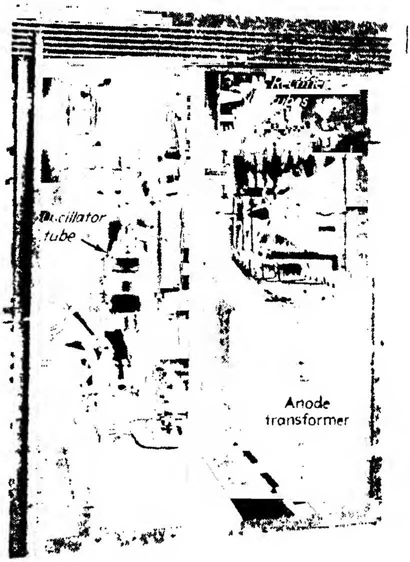


Fig. 20G View inside an electronic heater

electronic heater circuit, flowing through the turns of the load coil, causes a corresponding current to circulate within the work metal and produce heat inside the metal. Because of the high frequency, this current tends to flow mostly in the outside portions of the metal (because of "skin effect"), putting heat at desired spots.

Starting with the 60-cycle input, the electric power is first changed into a form of direct current before it is finally converted into high-frequency alternating current. These successive steps are shown in Fig. 20H, which also indicates the point in the circuit where these various waveshapes are likely to appear.

A simplified circuit diagram of the electronic heater appears in Fig. 20*I*. Here the 60-cycle power enters through transformer 1*T*, which supplies about 2500 volts at *AA*. (This voltage may be reduced in several steps by a tapped autotransformer, not shown.) This a-c supply is rectified by tubes 5, 6, 7 and 8, as is shown later, so that the voltage at *BB* is always in one direction, although still pulsating 120 times per second. At *CC* the oscillator tube 1 adds its high-frequency effect, producing a fluctuation, or "ripple," in the *BB* voltage.

Notice that tube 1 oscillates so rapidly that it converts each of the *BB* waves into more than 4500 ripples, or alternations. The

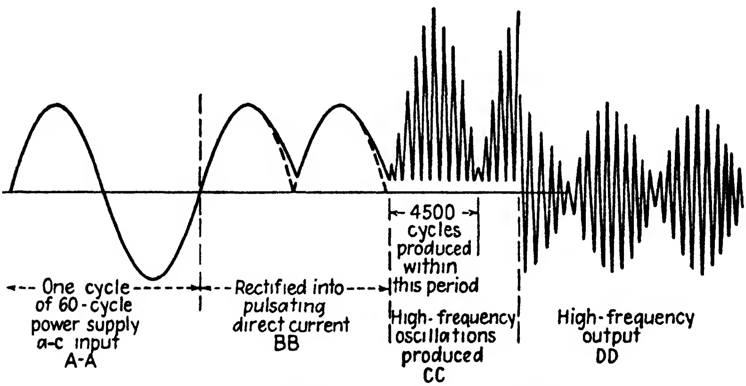


FIG. 20*H*. Steps in changing 60-cycle a.c. into high-frequency a.c.

resulting output *DD* is a voltage having 530,000 complete alternations each second. We may disregard the 120-cycle change of this voltage. Later, while we learn how the oscillator tube 1 works, we will assume that the voltage *BB* is held constant at its average value of about 2250 volts; the resulting high-frequency voltage *DD* will therefore be constant in height.

Tube 1 is the only oscillator tube shown in Fig. 20*I*. Four such tubes are included in the 5 kw (output) rating of the electronic heater; the 15-kw unit uses two tubes of greater rating. Such tubes are connected in parallel and operate as a group; therefore, we may select only one tube to represent this group in the simplified circuit.

The portion at the right in Fig. 20*I* is known as the "tank circuit"; it includes those capacitors (6*C* and 7*C*) and inductances (4*L* and the work coil) which control the output frequency of the

oscillator tube. As is shown later, a large alternating current circulates within this tank circuit at 530,000 cycles per second, and is quite separate from the current flowing in the oscillator and rectifier tubes.

20-6. The Four-tube Rectifier.—In Fig. 20*I*, tubes 5, 6, 7 and 8 form a rectifier of the full-wave bridge type, operating from a single phase of the 60-cycle power supply. Each of these tubes is a vapor-filled half-wave rectifier; it has no grid to control or limit the current flow. It is a heated tube, requiring that its

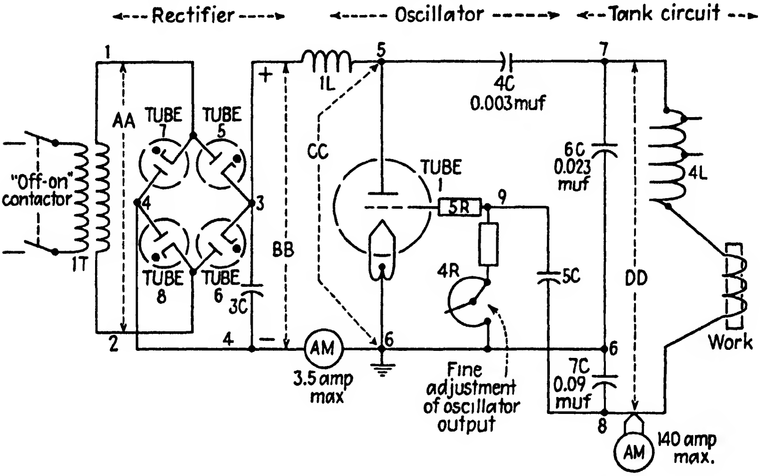


FIG. 20*I*.—Simplified circuit of an electronic heater.

filament be heated at least 5 min before attempting to pass anode current; any time thereafter these rectifier tubes supply current to the oscillator load as soon as the "off-on" contactor closes.

This rectifier circuit is like that of Fig. 10*J* and Sec. 10-8 (using disk rectifiers). When point 1 is positive, electrons flow from point 2 through tube 8 to point 4, through the ammeter to the oscillator circuit; electrons return through 1*L* to point 3, through tube 5 to point 1. (Notice that tubes 8 and 5 operate in series; only half of the high voltage *AA* is across each tube.) Similarly, when point 2 is positive, electrons flow from point 1 through tube 7 to point 4 and to the oscillator, then return through 1*L* to 3 through tube 6 to point 2. In either case, electrons flow from 4 toward 3 in the load or oscillator circuit; the voltage *BB* is pulsating but is always in the same direction.

20-7. First an Amplifier.—To lead up to the oscillator, let us first review how a high-vacuum tube, like oscillator tube 1, will respond to the potential at its grid; its anode current increases gradually as its grid potential becomes more positive.

If such a tube is connected as in Fig. 20*J*, the amount of direct current flowing in the tube and the primary of transformer *T* will depend upon the voltage *V* applied between the grid and the cathode. The operation of such a tube is shown in Fig. 20*K*; here we see that, with 2000 volts d.c. applied, about one ampere flows if the grid voltage is zero (as if the grid were connected to the cathode). If the grid is made 100 volts more positive than the cathode, the tube permits 2 amperes to flow. However, when the grid is made more negative than the cathode, the tube current decreases; a grid voltage of -100 volts can prevent all current flow.

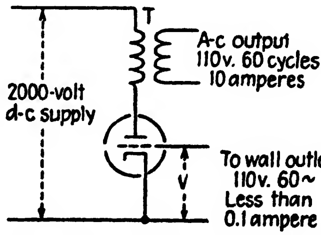


FIG. 20*J*.—Vacuum tube serving as a 60-cycle amplifier.

At *V* in Fig. 20*J*, suppose that we apply 110 volts, 60 cycles, as from a wall outlet. The grid of the vacuum tube now changes from positive to negative to positive 60 times each second; as shown in Fig. 20*L*, this causes a similar change in the tube current. By using the tube in this way, we convert a constant direct-current supply into almost a sine wave of current flow at 60 cycles. When this changing current flows through the primary winding of transformer *T* (in Fig. 20*J*) we find that the secondary of *T* can supply power to a 60-cycle a-c load of, say, 10 amperes at 110 volts. Here we see the tube working as an amplifier; we apply a tiny current at 110 volts to its grid, and the tube produces a useful output of 10 amperes at 110 volts, 60 cycles. So why not ask this question: Since the grid input and the load output are both at 110 volts, 60 cycles, why not use part of the

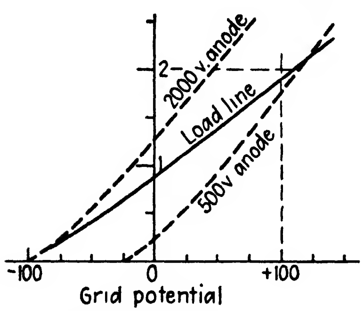


FIG. 20*K*.—Curves of grid potential versus anode current.

output to feed back to the grid, so that the wall plug is no longer required? In Fig. 20M, why not throw the switch from the lower to the upper position? If this is successful, the tube will be working as a 60-cycle oscillator, supplying its own grid voltage; no external grid signal is used

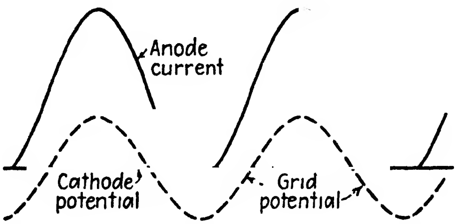


FIG. 20L.—Alternating grid potential causes waves of anode current.

20-8. A Simple Oscillator.—Such a trial will not be successful until we add a capacitor (C in Fig. 20M) of just the right size so that this capacitor has 60-cycle resonance with the inductance of transformer T. (This means that $1/2\pi fC$ must be equal to $2\pi fL$ where $f =$ 60 cycles, C is in farads, L is the transformer inductance in henries.) With C added, the circuit of Fig. 20M becomes a simple but uneconomical method of changing direct current into 60-cycle alternating current. However, if we now gradually reduce the size of capacitor C, the tube will oscillate faster, so that at this increased frequency C and L are still in resonance.

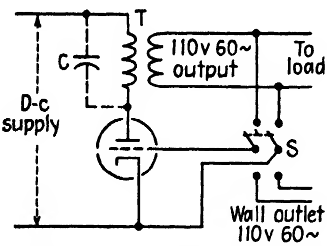


FIG. 20M.—Amplifier may become an oscillator when S is in upper position.

This is the basic explanation of the vacuum-tube oscillator; by proper selection of the amounts of L and C used in its output circuit, the tube will oscillate (alternately increase and decrease its anode current) at the desired frequency. This combination of L and C not only fixes the oscillating frequency, but also stores the energy necessary to supply a flow of power into the output circuit, even when the tube is not passing current continuously.

A mechanical illustration of such an oscillator is the grandfather's clock; its input, or driving force, is the steady pressure given by weights or a wound spring; its output is the swinging of

the pendulum. Steady pressure (like direct current) is converted into oscillating motion (like alternating current). The steady pressure may not be enough to start the pendulum from rest, but it keeps the pendulum swinging, because the pressure supplies the losses of the clock's movement. The length of the pendulum sets the rate of oscillation, or the frequency. Once each swing, the pendulum receives only a short "push" from the spring; the energy stored in the pendulum carries it through its complete swing and back to receive the next push.

20-9. Oscillator Action—Like a Rope Swing.—Let us return now to the oscillator circuit of Fig. 20*I*. As has been already mentioned, now we assume that the supply voltage *BB* is a constant d-c voltage; the low-frequency ripples from the 60-cycle supply are of no further interest. This constant d-c supply is the driving force that keeps the oscillator working. The real oscillation or high-frequency voltage appears at *DD*, and forces alternating current through the work. Several waves of this *DD* voltage are shown in Fig. 20*N*, together with corresponding voltages and currents in other parts of the circuit. Fig. 20*N* does not try to show what causes or controls the current flowing in tube 1; it shows the results when tube 1 passes current during short times, as shown.

Notice that the cathode-6 potential of the oscillator tube 1 is used as the center line, or axis, of the voltage diagram in Fig. 20*N*. The output voltage *DD* is shown swinging above and below this axis, causing a large alternating current (as much as 140 amperes in the 5-kw Electronic Heater) to flow in the tank circuit (6*C*, 7*C*, 1*L* and the work). This current meets resistance, so there are heat losses that absorb energy from the tank circuit. To replace these losses, oscillator tube 1 controls its flow of anode current so as to feed energy into the tank circuit; if these losses are not replaced, the voltage swing of *DD* decreases and soon all oscillation stops.

This circuit works quite like the rope swing under the apple tree. The swing continues to move back and forth for some time even after we stop pushing. While it "dies down," its number of forward movements per minute does not decrease (for its frequency remains constant, set only by the length of the rope); however, its travel away from the center point gradually decreases until all movement finally stops. The energy we

originally pushed into the swing has all been consumed in friction losses (heat).

To keep the swing in motion, a small push during each swinging movement is sufficient—merely enough push to overcome the losses. Also, rather than follow and push the swing gently during most of its travel arc, we know it is easier (more efficient) to stand still and give a sudden large push at the point where the swing is near the end of its travel, just starting to move forward.

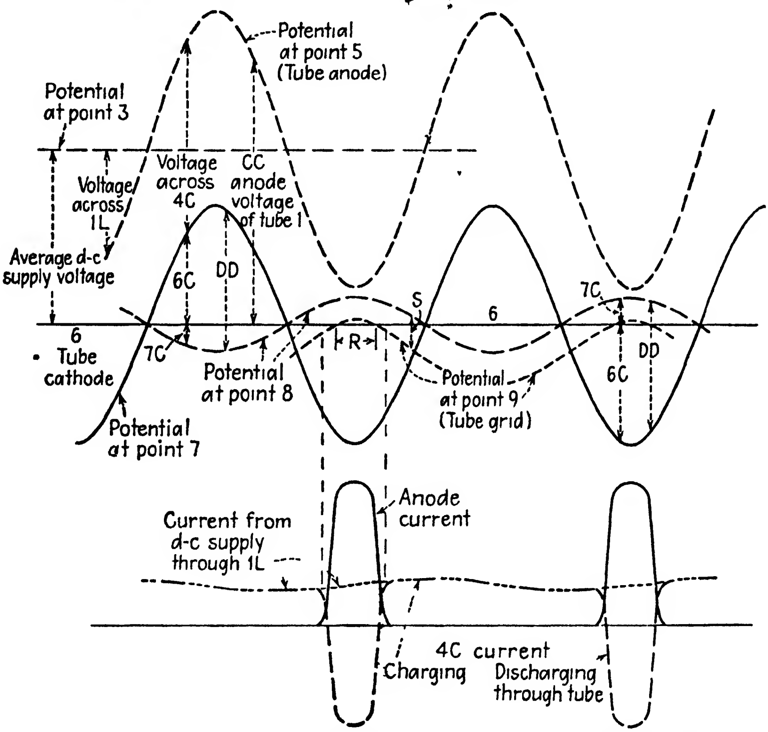


FIG. 20N.—Cyclic changes of voltage and current in the oscillator and tank circuits.

20-10. Tube and Tank Currents.—All these observations apply equally well to the oscillator. In the well-designed circuit, the oscillator tube permits anode current to flow during about one-fifth of each cycle. (We are speaking now of 530,000 cycles per second.) During the remaining four-fifths of the cycle, the current and voltage in the tank circuit continue their swings, but the tube rests.

From the d-c supply (*BB* in Fig. 20*I*) current flows continually through reactor 1*L* with very little change. During most of each cycle, these electrons flow from point 4 through the tank circuit and into capacitor 4*C*. This current delivers a small amount of energy into the tank circuit. When oscillator tube 1 permits anode current to flow, the steady flow through 1*L* now passes also through tube 1. At the same time, 4*C* discharges and forces a larger flow of electrons from point 7 through the tank circuit and tube 1. These currents are shown in Fig. 20*N*. Notice that this action is properly timed so that 4*C* forces* electrons into tank capacitor 6*C* (and back through tube 1) during the time when point 6 is more positive than point 7. This increases the voltage across 6*C* to replace its previous losses.

From the above operation we see that energy steadily leaves the d-c supply, but enters the tank circuit in pulses; the tank receives a small "push" from the flow of current that charges 4*C*, but it gets a larger "push" when 4*C* discharges through tube 1.

In Fig. 20*N*, the upper curve shows that the tube anode voltage *CC* is swinging to values greater and less than the average d-c supply voltage. By letting current flow through tube 1 only when the anode voltage is at the lower part of its swing, the losses in the tube are decreased (since watts loss equals tube current multiplied by anode voltage).

In Fig. 20*N* the distance between the large a-c curves shows the voltage across the capacitor 4*C*. Notice that this distance remains nearly constant; the potentials of points 5 and 7 (terminals of 4*C*) are swinging in equal amounts with relation to the axis (cathode 6 of tube 1). Although, as previously described, the direct-current supply flows steadily into 4*C* and then discharges suddenly through tube 1, the voltage across 4*C* changes very little (since 4*C* is selected large enough to give this result).

20-11. Grid Circuit of the Oscillator Tube.—We now should ask why the tank capacitor is built in two units (6*C* and 7*C* in

* To help in the above explanation, we show that 4*C* alternately receives and discharges current, so that 4*C* seems to be a necessary part of the oscillator circuit. Actually 4*C* has sufficient capacity so that it offers no barrier to the high-frequency alternating current flowing between the tank circuit and the tube anode. The tube oscillates well, even if 4*C* is shorted; 4*C* merely insulates or blocks the high d-c supply voltage from the tank circuit, so that this high voltage cannot reach the work coil.

Fig. 20*I*) instead of being combined into one unit having that size needed to give the desired output frequency. These two capacitors split the rf (radio-frequency or high-frequency) voltage *DD* into two parts. The voltage across 7*C* is used to give a signal back to tube-1 grid so that this oscillator tube will let its anode current "push" the tank circuit at the right instant to maintain oscillation.

In Fig. 20*N* we see that the voltage across 7*C* is about one-fourth as large as the voltage across 6*C*. Of greater importance, the 7*C* voltage is 180 degrees out of phase with the 6*C* voltage, so that point 8 is above the axis (point 6) whenever point 7 is below the axis. Point 8 is connected (through 5*C* and 5*R*) to the grid of tube 1, and Fig. 20*N* shows that the 7*C* voltage tends to make the tube grid more positive (thereby permitting anode current to flow) during the half cycle when there is the smallest tube anode voltage *CC*.

The potential at tube-1 grid (at point 9 in Fig. 20*N*) is seen to be a voltage wave of shape similar to that of point 8 but at a lower level, so that the grid is positive (above point 6, cathode of tube 1) only during the brief time marked *R*. This downward displacement of the grid potential (shown as *S* in Fig. 20*N*) is caused by the voltage across 5*C* in the grid circuit (in Fig. 20*I*): this voltage *S* is known as the *grid bias*.[6-8] We next need to learn how this grid bias is produced, and how it controls the power output of the electronic heater.

20-12. Effect of the Grid Bias.—During any instant when the tube-1 grid is more positive than the cathode, electrons can flow through the tube from cathode to grid. The voltage across 7*C* (see Fig. 20*I*) forces these electrons to flow from point 6, through the tube to the grid connection, through 5*R* into capacitor 5*C* and back to 7*C*. This flow tends to charge 5*C* to the crest, or peak, value of the 7*C* voltage. When the grid voltage next swings negative (below point 6, the cathode) this grid current stops, leaving 5*C* charged. During the following half cycle (when the 7*C* voltage has reversed, so that point 6 is more positive than point 8), the rectifying action of the tube prevents electrons from flowing in the grid-to-cathode direction, which could discharge 5*C*. However, a discharge path is provided through the adjustable resistor 4*R*, so that 5*C* loses a small part of its charge and voltage before the start of the next cycle. (The

voltages of $5C$ and $7C$ combine to cause this flow of electrons from point 9 through $4R$ to point 6.) If $4R$ is turned, decreasing its resistance, the $5C$ voltage decreases more rapidly than before.

This action in the grid circuit is shown in the upper right-hand part of Fig. 20O. Here we see how the tube-1 grid is positive during the brief time R, which is just long enough for the flow of grid current to restore the charge on $5C$ to its largest value

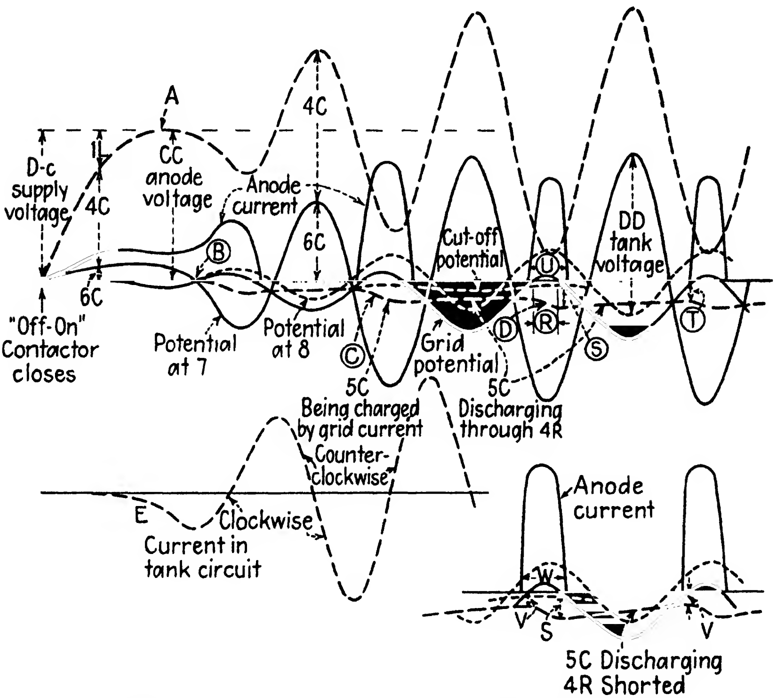


FIG. 20O. Curves showing buildup of oscillation and self-bias.

S. $5C$ then slowly discharges through $4R$ (which is set here for largest resistance) until it has reached a value T by the next time the grid current flows.

Meanwhile, anode current flows in tube 1 when the grid potential is above the cutoff value.[3-11] (As shown in Fig. 20K, cutoff is about -25 volts when the anode voltage is 500 volts; cutoff is -100 volts when anode voltage is 2000 volts.) Because of this bias voltage S or T, the grid potential prevents the flow of anode current except during time U. The amount of "push" that tube

1 delivers to the tank circuit during this short time U may not be enough to supply the losses of a large heating-coil load, and the oscillation may stop. However, by decreasing the resistance of $4R$, we are able to increase the output to the heating coil, as is next shown.

In the lower part of Fig. 20*O* we see the action with $4R$ shorted; $5C$ now loses its charge more rapidly, so that the bias decreases to the amount V. We see that V is much less than T (above); the curve of grid potential crosses the cutoff line earlier and permits anode current to flow in tube 1 during a longer time W. Also, since the grid potential becomes more positive than before, the amount of momentary anode current is increased, permitted by a greater discharge current from $4C$. The result is a greater "push" by tube 1—the delivery of greater energy into the tank circuit and greater output to the heating coil.

20-13. The Start of Oscillation.—As a matter of further interest, Fig. 20*O* shows that this oscillator is self-starting, and also shows how tube 1 produces its "self-bias." Any time after the 5-min tube-warming period, the electronic heater is made to produce its output merely by closing the "off-on" contactor (in Fig. 20*I*). Just as this contactor closes, there is no charge on $4C$, $5C$, $6C$ or $7C$; the grid of tube 1 is at the same potential as the cathode, so there is no bias to prevent current flow in the tube

The closing contacts apply the d-c supply voltage to $1L$, $4C$ and $6C$ in series. As the current flow increases through $1L$ and charges $4C$ and $6C$, the voltage across $4C$ becomes nearly as great as the d-c supply voltage, as shown at A in Fig. 20*O*. This increasing voltage is also applied to the anode of tube 1, which permits current to flow through the tube. The small voltage across $6C$ causes current E to flow in $4L$ and the work coil, and the tank circuit begins to oscillate; its voltage waves become higher and higher.

When the tube-1 grid first becomes positive, as shown at B, grid current charges $5C$ to a small voltage; this voltage mostly remains across $5C$ until it is further increased by grid current flowing at point C. Assuming that, upon reaching point D, the tank circuit is now oscillating at nearly full amount, capacitor $5C$ gets its full charge S, which, added to the alternating voltage at point 8, keeps tube-1 grid negative except during time R. We see that this bias voltage across $5C$ has been produced by tube 1

itself, because of the oscillating tank-circuit voltages that tube 1 maintains; this explains the term "self-bias." When oscillation stops for any reason, the bias voltage of 5C drains away.

20-14. Main Oscillator Features.—A tube circuit of the feed-back type (including that of the electronic heater above) must include certain features before it will oscillate. (1) The tube must amplify; there must be enough change or swing of anode power output, so that part of this may be used to supply the grid input power and still have enough left to supply all circuit losses and the outside load. (2) Enough energy must be stored in the tank circuit (capacitors and inductances) to furnish all power needed by the load during the time when the oscillator tube is not passing current. (3) The voltage wave or signal at the oscillator-tube grid must be 180 deg out of phase with the wave of anode voltage —the grid is most positive when the anode is least positive.

The oscillator frequency depends on the size of the combined capacity and inductance in the tank circuit. Therefore, the output frequency $f = 1/2\pi\sqrt{LC}$* (where L is in henries, C is in farads, f is in cycles per second).

20-15. Class A, B or C Operation.—In the electronic-heater circuit (Fig. 20I), tube 1 is working as a Class-C oscillator. By "Class-C" operation (used in the tube rating) we merely indicate that anode current flows in tube 1 during much less than one-half of each cycle. This can be seen in Fig. 20N or Fig. 20O; with such operation, less energy is lost in the tube. In comparison, Class-A operation means that some current may flow in the tube during its entire cycle. These classes of tube operation are shown in Fig. 20P, which applies to tubes working as amplifiers or as oscillators. The lower part of Fig. 20P shows the signal voltage applied to the grid; each signal causes its own kind of anode-current response, as reflected from the load line of the tube (see Fig. 7D). Often the same tube may be used in Class-A, Class-B or Class-C operation; the tube does not change; only its method of use changes, depending on the grid bias.

For Class A a small bias is used, so that the signal produces a grid potential that is always between zero and cutoff; the anode current has about the same waveshape as the grid signal and

* At resonance,[20-8] $2\pi fL$ must equal $1/2\pi fC$, so $f^2 = 1/(2\pi L)(2\pi C)$, or $f = \sqrt{1/(2\pi L)(2\pi C)} = 1/2\pi\sqrt{LC}$. Similarly, for high-frequency work, frequency in kilocycles $= 1{,}000{,}000/2\pi\sqrt{\mu H \times \mu\mu fd.}$

rarely drops to zero. Where the waveshape of each cycle is important, as in af (audio- or sound-frequency) circuits, Class-A operation is often used. The rating of a tube in Class-A operation is like the continuous rating of a motor.

For Class B, the tube is "biased at cutoff"; with no signal, there is no anode current. Since the grid signal swings equally above and below cutoff, anode current may flow for half of each

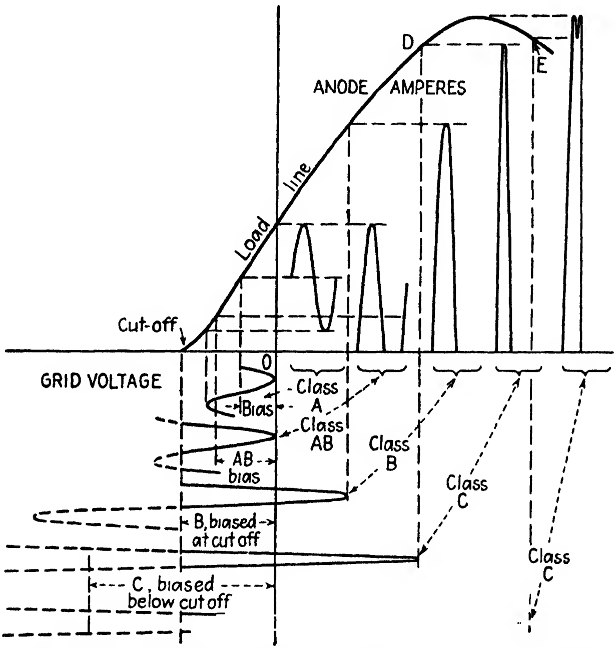


FIG. 20P. Grid bias determines Class A, B or C operation.

cycle. A large signal voltage is used, so that the grid becomes positive, causing much larger flow of anode current. In Class-B operation, since anode current flows during only half of the time, a tube has a higher current rating than in Class-A operation. Class AB is partway between Class A and Class B; the grid does not become positive, but anode current does not flow during the entire cycle.

For Class C the tube is biased below cutoff; only a part of the positive swing of the grid signal causes anode current to flow; this is the condition shown in Fig. 20O. At D in Fig. 20P, notice that the signal voltage has forced the grid more positive (than in

Class B), but D is still on the rising portion of the load line, so the anode-current waveshape has a single peak. However, when the signal voltage is increased further, the tube operates at E, beyond the "hump" on the load line; this produces an anode-current waveshape having a notch in the top, or two peaks per cycle. Most industrial oscillator tubes have Class-C operation.

20-16. Push-pull Operation.—An amplifier or an oscillator circuit may use more than one tube, connected in parallel, as shown by the simplified circuit in Fig. 20Q; all such tubes receive the same grid-voltage signal, so the tubes divide the anode current between them.

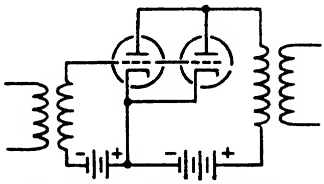


FIG. 20Q.—Tubes operating in parallel.

Two tubes may be "connected in push-pull," as shown in Fig. 20R. Working as an amplifier circuit, the grid voltage supplied by transformer 1T drives the tube-A grid positive at the same time that it drives the tube-B grid negative; therefore, the tubes fire in turn. First electrons flow from the d-c-supply terminal 1, cathode to anode through tube A, down through the upper half of the output transformer 2T to terminal 2; this is the "push" in 2T. When the grid signal reverses, electrons flow from 1 through tube B and up through the lower half of 2T, to 2; this is the "pull," for it reverses the current flow in 2T.

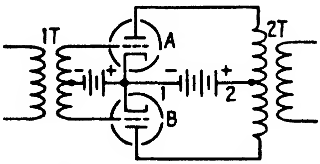


FIG. 20R. Tubes operating in push-pull.

In push-pull, each tube may pass current during only half of the cycle, yet the combined tube output (through 2T) may have the same waveshape as the input grid signal. In this way, two tubes may operate Class B, giving as good output waveshape as a single tube operating Class A.

20-17. Elevator-car-leveling Oscillator.—As an example of the oscillator used as an off-on device,[20-4] electric elevator cars in office buildings may be slowed and stopped at floor level by such oscillators. The complete oscillator (whose circuit appears in Fig. 20S) is mounted on top of the elevator car and moves with the car; the two coils 2L and 3L of the oscillator circuit project side by side from the oscillator box, with about an inch of space

between the coils. When the car nears a floor, the coils pass on both sides of a steel vane fastened in the elevator shaft; this vane stops the oscillator, so that a relay *CR* opens a power circuit to the elevator motor.

In Fig. 20*S* tube 1 oscillates (with rapid changes of anode current) when no steel vane is between coils 2*L* and 3*L*. These coils work together as in a transformer; when the tube-1 anode current changes, the voltage across coil 2*L* changes, and this change causes a similar voltage to appear across 3*L*. Part of the output voltage (across 2*L*) is fed back to the grid (at 3*L*), so this is a feed-back type of oscillator. Instead of using a capacitor connected across 2*L*, capacitor 3*C* is connected across 3*L* in

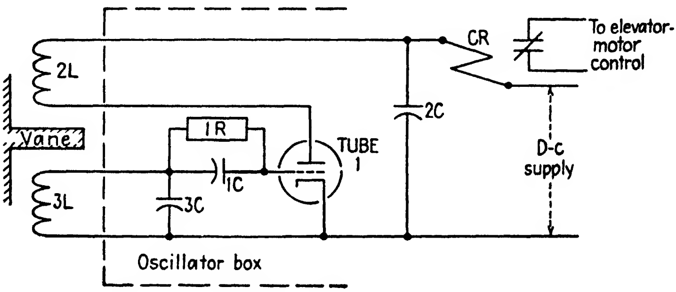


FIG. 20*S*.—Oscillator for elevator-car leveling.

the grid circuit. This is also called a "tuned-grid" oscillator; the size of 3*C* and 3*L* sets the output frequency.

The grid circuit makes its own bias across 1*R* and 1*C* (which act like 4*R* and 5*C* in Fig. 20*I*). Because of this bias, the tube operates Class C,[20-15] so that anode current flows during only a small part of each oscillating cycle. Also, since this anode current changes so rapidly, the inductance of 2*L* prevents much flow of current. While oscillating, the average anode current is about 1 ma, which is not enough to pick up the relay *CR*.

When the steel vane is in the space between coils 2*L* and 3*L*, this metal prevents the changing 2*L* voltage from affecting 3*L*; 3*L* produces no voltage in the grid circuit, so the oscillation stops (as the motion of the rope swing "dies down" when you stop pushing). The bias voltage across 1*C* drains away through 1*R*. Tube 1 now passes current steadily; this direct current passes easily through the inductance of 2*L*. The average tube-1 anode

current increases greatly when oscillation stops; it rises to about 15 ma, which easily picks up relay *CR* to control the elevator motor.*

When the car starts again, coils 2*L* and 3*L* move away from the steel vane; oscillation starts and the tube-1 anode current decreases, dropping out relay *CR*.

An oscillator is used in this same way when it is included in certain instruments; a small metal vane is mounted on the moving needle of the instrument. When this vane passes between two tiny coils (which have been set at the desired operating point on the instrument scale), the oscillator stops and a relay operates. The moving needle touches no other part, yet it may control an electric circuit of many amperes.

A piece of metal placed near an inductance in an oscillator circuit may nearly stop the oscillation; another piece, very slightly different, may stop the oscillator entirely. In this way, an oscillator circuit may be a very sensitive indicator of the condition of metals.

20-18. Standard Oscillator Types.—Rather than describe other oscillator circuits in detail, we shall sketch below several well-known types, in the hope that they will invite you to study them in more complete texts.

A Colpitts oscillator is shown in Fig. 20*T*, in the form used in many texts. Its parts are numbered the same as in the electronic heater (Fig. 20*I*), which is also a Colpitts oscillator. This type is recognized by the tank circuit consisting of two capacitor groups (6*C* and 7*C*) and a single continuous inductance (4*L* and work coil combined). This inductance is the path by which part of the anode output is fed back to the grid.

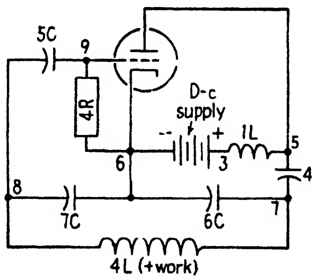


FIG. 20*T*.—Colpitts oscillator.

A Hartley oscillator (Fig. 20*U*) is like the Colpitts, except that the tank circuit uses two inductances (2*L* and 3*L*, or a single inductance with a tap connecting to the tube cathode), and a single capacitor 2*C*. For the dielectric heating[19-7] of nonmetals, the material to be heated is placed between two metal plates,

* Several such oscillators are used on each elevator car, with separate steel vanes placed to give various control actions.

which act as the two sides of capacitor $2C$. The tank circuit feeds part of the anode output back to the grid.

The oscillator circuit of Fig. 20V looks like Fig. 20U, except that there are two capacitors $4C$ and $5C$ instead of $2C$ alone. In the grid circuit, $5C$ and $5L$ are chosen so they are resonant[20-8] at the desired output frequency; $4C$ and $4L$ are similarly chosen so they are resonant at this same output frequency. This is a

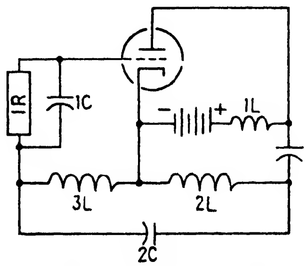


FIG. 20U.—Hartley oscillator.

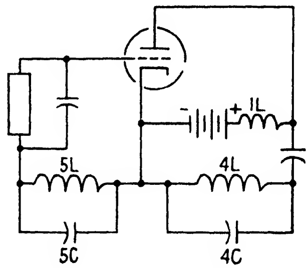


FIG. 20V. Tuned-grid tuned-plate oscillator.

tuned-grid, tuned-plate oscillator. Here $4L$ and $5L$ are separate inductances and there is no transformer action between them; therefore, how does the grid circuit receive the voltage signal from the anode or plate circuit, so that the tube will oscillate? The necessary grid signal passes through the tube, directly from anode to grid, because these parts of the tube act like a capacitor (see Sec. 7-6, footnote). This "interelectrode capacity" lets the rapid changes of anode voltage cause similar voltage changes at the grid; in this way, part of the anode output voltage is fed back to the grid, through the tube itself.

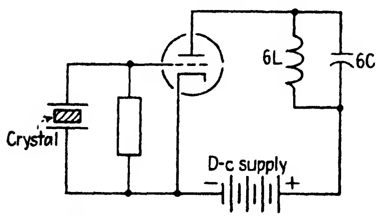


FIG. 20W.—Crystal-controlled oscillator.

The output frequency of most oscillators may change when the load varies. While this frequency drift may have little effect on the results produced by oscillators used in industry, government regulations may require that the output frequency be held more constant. More constant frequency is produced by a *crystal-controlled* oscillator. As is shown in Fig. 20W, such an oscillator may be quite like Fig. 20V, for the crystal takes the place of the tuned-grid circuit. This crystal is a thin piece of quartz

that has been accurately cut and finished to the desired thickness; this thickness sets the oscillator frequency. The crystal is mounted between two metal surfaces; when low voltage is applied between these two surfaces, the crystal expands or contracts. In the circuit of Fig. 20*W*, the tiny changes of grid voltage (fed back between anode and grid within the tube) make the crystal vibrate. Greatest vibration occurs at just one frequency for each crystal; the crystal acts like a capacitor and inductance that are tuned, or resonant, at that one frequency. If 6*L* and 6*C* are also resonant at this crystal frequency, the circuit oscillates. The crystal vibration decreases sharply if the frequency changes a tiny amount; therefore, such a crystal-controlled oscillator holds the frequency within narrow limits.

Questions

True or false? Explain why.

1. If capacitor *C* is shorted, in Fig. 20*A*, tube 1 fires steadily.

2. If 4*R* is burned open, in Fig. 20*E*, tube 1 fires as long as *S* is closed.

3. If the inverter of Fig. 20*A* has an output of 500 cycles per second, the deionization time of the thyratron needs to be only as short as $^1\!/_{1000}$ sec.

4. The parallel inverter of Fig. 20*D* works in push-pull.

5. The inverter of Fig. 20*A* works even when there is no energy stored in its circuit.

6. A tank circuit may contain only inductance and resistance.

7. An oscillator is not self-starting if a fixed voltage (such as a battery) is used to bias the tube below cutoff.

8. The Hartley and Colpitts circuits are types of feed-back oscillator.

9. If the tube in the oscillator of Fig. 20*V* is replaced with a pentode (with its extra grids connected for pentode operation), the circuit will not oscillate.

10. The anode voltage of an oscillator tube may rise higher than the d-c supply voltage.

11. All Hartley oscillators operate from batteries.

12. When a tube is operating Class B, you may double its bias and get Class-C operation.

13. An oscillating circuit stores energy in two different forms; this energy rapidly changes from one form into the other, and back again.

14. The output of tubes operating Class B never has the same waveshape as the input grid signal.

CHAPTER 21

TEMPERATURE RECORDERS

Electronic circuits help to make a record chart of changing temperatures, accurate within part of a degree. Such temperature recorders* must respond when the input voltage changes less than 1/10,000 volt, and must amplify this signal until it can run a motor to drive a recording pen. These amplifier circuits may respond to tiny voltage changes caused when some other circuit becomes slightly unbalanced; since the amplifier makes the motor turn in the right direction to bring the circuit back to a balanced condition, it is called a self-balancing circuit.† Similar circuits are used in airplane controls, as in one kind of auto-pilot.

21-1. A Change of 0.0001 Volt Turns a Motor.—One kind of temperature recorder (whose amplifier circuit is described later) uses a thermocouple to "tell" how hot the furnace or the metal is. As is mentioned in Sec. 28-14, this thermocouple has two pieces of different metals, which are joined at one end; this end, when hot, produces a tiny voltage. This d-c voltage changes less than 1/10,000 volt (or 1/10 millivolt) for each 10-degree change in temperature. Such a thermocouple is included in Fig. 21*A*, which shows the main parts of the recorder.

Instead of directly amplifying this 1/10-millivolt change, most electronic-circuit designers prefer to convert such a d-c signal into an alternating or changing signal, for it then can be amplified more easily. So in Fig. 21*A* a converter receives the d-c signal from the thermocouple and produces a tiny a-c signal at trans-

* A similar temperature instrument is used with the furnace-heating circuit described in Sec. 14-8.

† Such equipments are also *servomechanisms* or positioning controls; when such a "servo" detects a very small change in voltage (or position, speed, etc.), it controls some larger device (such as a motor, valve, or solenoid) to get the large force needed to correct conditions, until the changed voltage or signal is brought back to the starting point. Each of us may be part of a servo; when the "boss" gives an order to do a certain job, the workers are the mechanism that applies the force until the order is met or satisfied.

former T; after passing through several electronic amplifier circuits, this a-c signal becomes a voltage strong enough (at H) to make a motor turn. This balancing motor is geared to the recording pen (not shown); the motor also moves the slider at 4 along a slide wire, until the voltage V is exactly equal to the thermocouple voltage.

The converter is merely a metal reed, which is made to move up and down 60 times per second, being driven by a 60-cycle coil E. For a moment, suppose this reed is held upward so that it closes the circuit to contact 1. Now if the thermocouple produces a greater voltage (than battery B produces at V), this thermocouple voltage forces electrons to flow from 5 through 1R and slider 4, to contact 1, down through the upper half of T to mid-point 3, back to the thermocouple. However, if we move slider 4 to the right until voltage V becomes exactly equal to the thermocouple voltage, notice that these two voltages oppose each other, so that no voltage remains in the converter circuit; no current flows in T.

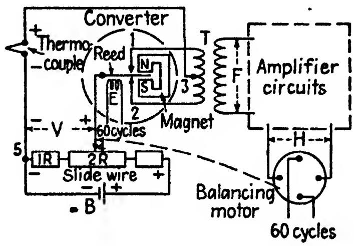


FIG. 21A.—Thermocouple voltage is converted and amplified to turn a motor.

If slider 4 is moved still farther to the right, voltage V now forces electrons to flow up through the thermocouple to mid-point 3, up through T to contact 1, back to 4. We see that electrons flow from 4 up into contact 1 when V is less than the thermocouple voltage.

The metal reed of the converter touches upper contact 1 during each positive half cycle of the a-c power supply. (This a-c wave is shown in curves 1 and 8 of Fig. 21B.) To see why the reed moves upward, notice that the permanent magnet has a North upper pole; during the up half cycle, current flows in coil E in that direction which magnetizes the reed so that its right-hand end is a South pole, which is therefore attracted upward. A half cycle later, current has reversed in coil E, and now produces a North pole at the right-hand end of the reed; the reed is pulled down by the South or lower pole of the permanent magnet.

When the reed touches lower contact 2, the electrons (which had been flowing up into contact 1) flow now into contact 2,

upward through transformer T to midtap 3. Notice that, as long as V is less than the thermocouple voltage, the electrons flow through T always toward the midtap, and alternately through the upper and lower halves of the primary winding of T. Meanwhile, the secondary of T produces an a-c voltage wave (shown at curve 2 of Fig. 21B), which is fed to the amplifier. This makes the motor turn (say, clockwise, as explained later), and moves slider 4 toward the right; this increases voltage V until it becomes equal to the thermocouple voltage. When these voltages balance, no voltage remains at T, so there is no voltage at H to turn the motor. Although the reed still vibrates, there is no motor movement while V is in balance with the thermocouple voltage.

However, when the slider is too far to the right, so that V is greater than the thermocouple voltage, electrons flow away from midtap 3 through transformer T, out of contacts 1 and 2 toward the slide wire. The resulting voltage that T produces at F, is shown by curve 9 of Fig. 21B; curve 9 is reversed, or 180 deg out of phase with timing wave 8, whereas curve 2 is in phase with the timing wave. Let us now see how these signals (curve 2 or curve 9) are amplified so as to turn the motor.

21-2. The Brown Continuous-balance Potentiometer.—The amplifier circuit of this temperature instrument is shown in Fig. 21C. The input signal at F is the a-c wave (curve 2 or 9 of Fig. 21B) described above. Three twin-triode[17-11] tubes are used in the amplifier, and they are shown as six separate tube circles; circles A and AA are parts of the same tube. A-c supply power is received through the transformer (upper right in Fig. 21C), which also furnishes the timing wave E for the converter. One triode BB acts as a diode rectifier to furnish d-c voltage between points 6 and 7 (filtered by capacitor 1C). Amplifiers A, AA and B receive d-c anode voltage from this supply.

When there is no signal voltage at F (as when voltage V is equal to the thermocouple voltage), the grid 8 of tube A seems to be at the same potential as cathode 9. However, this lets tube A pass current; these electrons flow from 7 through 4R, tube A, 3R and 6R to 6. A voltage appears across 4R [(−) at 7, (+) at 9], which makes cathode 9 more positive than grid 8, decreasing the tube-A current. This voltage across 4R is the grid bias of tube A. With no grid signal, tube A passes a small steady current, producing

also a voltage drop across $3R$. However, no matter what steady voltage appears between points 10 and 7, capacitor $2C$ charges to this voltage, and no voltage remains across resistor $5R$. The grid of tube AA is at the same potential as its cathode, so tube AA is passing steady anode current. However, this has no effect on tube B, for capacitor $4C$ has charged to the voltage between points 13 and 7 so that no voltage remains across $8R$. Tube B also has zero grid voltage and passes some anode current. Simi-

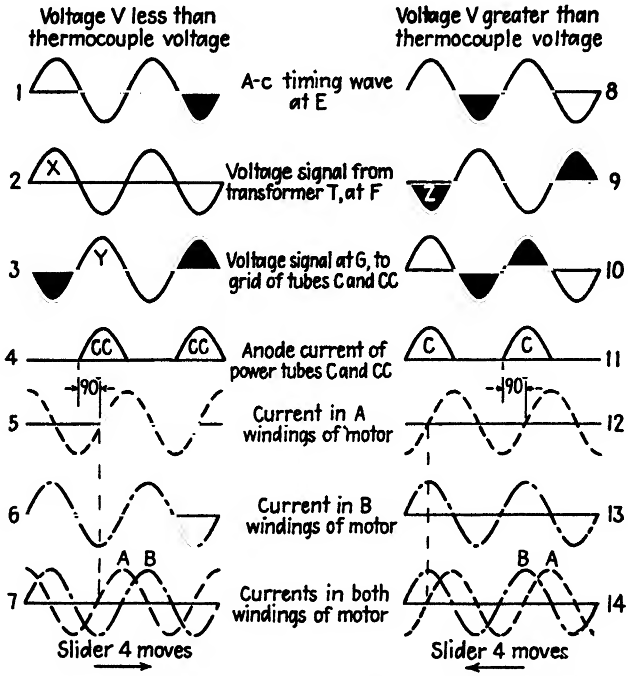


FIG. 21B.—Voltage signals and motor-current waves in Fig. 21C.

larly, $5C$ has charged to the voltage 15-to-7, and grid 16 of both tubes C and CC is at the same potential as point 7.

In Fig. 21C tubes C and CC are not in parallel; although their cathodes are together and their grids are together, their anodes are at opposite ends of a transformer winding. Tube C may fire during one half cycle, tube CC during the next half cycle; never do both tubes pass current at the same time. While their grids 16 remain at point-7 potential, tubes C and CC act as a two-tube rectifier, producing a small direct current; these electrons flow

from 18 through the A windings of the motor to 7, through $11R$ to cathodes 17, and through tubes C and CC in turn. (The voltage across $11R$ makes cathodes 17 more positive than grids 16; acting as a grid bias, this limits the amount of anode current of tubes C and CC.) This direct current through the motor windings does not turn the motor, which is an a-c induction motor. So, until a signal voltage appears at F in Fig. 21C, all tubes pass current steadily but the motor does not turn.

21-3. Capacitor-coupled Amplifiers.—In Fig. 21C, suppose that the furnace temperature rises, increasing the thermocouple

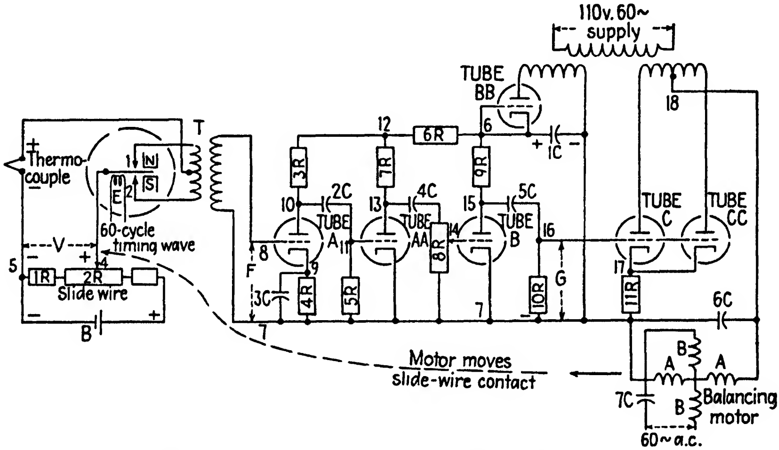


FIG. 21C.—The Brown Continuous-balance Potentiometer.

voltage; voltage V is now less than thermocouple voltage, so a signal voltage appears at F, as shown in curve 2 in Fig. 21B. During the half wave X, grid 8 becomes more positive, increasing the tube-A anode current. This reduces the potential at 10; since capacitor $2C$ cannot change its charge instantly, the potential at 11 is forced more negative. Since the grid voltage of tube AA becomes negative, its anode current decreases. Notice that more tube-A current causes less tube-AA current; this action is like the direct-coupled amplifiers described in Sec. 15-9. However, only a fast change in tube-A current can affect tube AA; if the tube-A current changes so slowly that the charge on capacitor $2C$ can also change, the tube-AA current does not change. Since the signal at F is a fast-changing a-c wave, the fast changes of potential at 10 also reach the grid of tube AA; tube AA is

coupled to tube A by capacitor $2C$. Similarly, capacitor $4C$ couples tubes AA and B. When current decreases in tube AA, it increases in tube B; as point 13 rises, capacitor $4C$ tries to charge to the increasing voltage 13-to-7; the $4C$ charging current causes a voltage drop across $8R$, so that point 14 (grid of tube B) becomes more positive than cathode 7. The slider on $8R$ is a sensitivity control; when it is moved toward the lower end, less of the voltage across $8R$ is used to change the tube-B current, so the whole amplifier has less output at G.

During half wave X, when current increases in tube A, decreases in tube AA and increases in tube B, the potential at 15 drops.* Coupled through capacitor $5C$, the potential at point 16 is now more negative than point 7. Curve 3 of Fig. 21B shows this change at 16, and is also the grid voltage of tubes C and CC. During half cycle X, the tube-C anode is positive, tube-CC anode is negative; neither tube passes current, since the voltage of both grids is negative. However, during the next half cycle, these grids are positive (as shown at Y in Fig. 21B); although both grids are positive, only tube CC passes current, for the tube-C anode is now negative. The amount of this tube-CC current increases if the voltage signal (curve 2) becomes larger.

21-4. Running the Balancing Motor.—From the above, we see that tube CC passes half-cycle pulses of current whenever voltage V is less than the thermocouple voltage. These current pulses (curve 4 in Fig. 21B) must be changed into an alternating current before they reach the motor winding. To do this, capacitor $6C$ is added (in Fig. 21C), which is large enough to be resonant (at 60 cycles)[20-8] with the inductance of the motor windings A. Current now flows back and forth in windings A, and in and out of capacitor $6C$. Of course, this alternating current is started and kept flowing because of the pulses from tube CC. Similarly, although you give short sudden pushes to a rope swing, the swing moves smoothly back and forth (like a sine wave of current). You push the swing where it is barely moving, at a point near one limit of its travel; the swing reaches full speed later, at the middle

* Tubes A, AA and B give three stages of voltage amplification, increasing the signal voltage in three steps. If input voltage F is $\frac{1}{1000}$ volt a.c., the tube-AA grid voltage (across $5R$) is perhaps $\frac{1}{25}$ volt; the tube-B grid voltage (across $8R$) may be 1 to 2 volts, so that perhaps 10 to 30 volts can be used at G, to control the power amplifiers C and CC.

of its travel. Similarly, when tube *CC* "pushes" the swinging circuit (of 6*C* and windings *A*), the greatest current flows in this circuit about 90 degrees after the push; the wave of current in the *A* motor winding (curve 5 of Fig. 21*B*) lags 90 degrees behind the wave of tube-*CC* current (curve 4).*

This balancing motor in Fig. 21*C* is a two-winding induction motor (like those operated on two-phase a-c power supply). The motor does not turn unless a.c. flows in both its windings. The *B* windings are connected to the a-c supply, so that alternating current always flows. Since this winding is inductive, its current lags behind the voltage; capacitor 7*C* is added so that the current in the *B* windings is kept in phase with the a-c supply voltage, as shown in curves 6 and 13 of Fig. 21*B*.

When tube *CC* alone passes current, the current in the motor's *A* windings is shown by curve 5. This is shown again in curve 7, which also includes curve 6 (current in the *B* windings). Notice that the *A*-winding current is to the left of the *B*-winding current and leads by 90 degrees; these combined currents make this induction motor turn so as to move slider 4 toward the right.

When the furnace cools so that voltage *V* becomes larger than the thermocouple voltage, the signal voltage at *F* becomes like curve 9 of Fig. 21*B*. Notice that, during the half cycle *Z* when the converter reed is up, touching contact 1, the voltage at *F* is now negative—opposite to the curve-2 condition. Since grid 8 is made negative during this half wave, tube-*A* current decreases, tube-*AA* current increases, tube-*B* current decreases, and the signal at *G* becomes more positive, as shown in curve 10. During half wave *Z*, the grids of tubes *C* and *CC* are both positive; however, the anode of tube *CC* is negative during this half cycle, so tube *CC* passes no current. The tube-*C* anode is positive during half cycle *Z*, so tube *C* may pass pulses of current. These pulses make alternating current flow in the motor's *A* winding and resonant capacitor 6*C*, as before; this alternating current (curve 12) lags 90 degrees behind the wave of tube-*C* current (curve 11). However, since the tube-*C* pulses occur a half cycle later (than the tube-*CC* pulses of curve 4), the wave of current in the *A* windings is also later. In the combined curves 14, we see

* The current in the *A* winding includes some direct current; this is not shown in curves 5 or 12, since this direct current does not help to turn the motor.

that the A-winding current is to the right of the B-winding current, and lags by 90 degrees. These combined currents make the induction motor turn so as to move slider 4 toward the left.

From this study of Fig. 21C, we realize that the timing wave E (which drives the converter reed) must always be in step with the a-c voltage wave applied to power tubes C and CC. Note also that the motor begins to turn instantly to bring the slider to the required position of balance; this provides a continuous-balance feature. Figure 21C omits many parts or circuit features that are included in this continuous-balance potentiometer.

21-5. A-c Bridge Signal for the Amplifier.—The continuous-balance type of amplifier may also receive its signal from an a-c bridge or potentiometer circuit, such as is shown in Fig. 21D; any

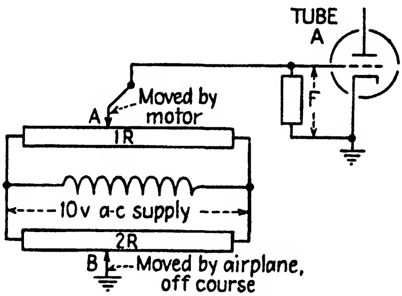


FIG. 21D.—A-c bridge circuit controls amplifier A.

voltage unbalance in such a circuit gives a signal that is an a-c voltage, and therefore does not need a converter such as is used with the thermocouple in Fig. 21A. In Fig. 21D, resistors 1R and 2R are both connected across an a-c voltage (which must be supplied by the same generator or system that feeds the power tubes and motor of the main amplifier circuit). All of Fig. 21D is in the grid circuit of the first amplifier tube (such as tube A of Fig. 21C).

When slider A is exactly above slider B, there is no voltage between these sliders and no a-c signal is given to the tube at F. But suppose that, inside an airplane, resistor 2R is fastened so that its slider B is moved slightly to the left when the airplane starts to get off its course. Perhaps slider B moves so little that its potential changes only $\frac{1}{10}$ volt, yet this produces an a-c wave of $\frac{1}{10}$ volt at F. As described above, this a-c voltage is strength-

ened in the amplifier circuit until it can operate a motor or a valve; this device moves the flaps or the rudder to bring the plane back on its course, and it also moves slider *A* to the left until the two sliders are again in line, with zero voltage between them.

In another design of temperature recorder, an a-c bridge circuit is used in place of the thermocouple and converter of Fig. 21*A*. As shown at the left in Fig. 21*E*, this bridge includes fixed resistors *A*, *B*, *R* and *S*; resistance *T* is made of platinum and is placed in the hot furnace. When the furnace temperature rises, the resistance of *T* increases. Since these resistors are connected across an a-c supply voltage (between points 3 and 4) there is some a-c voltage across each resistor. When *T* becomes hotter, the amount of voltage across *T* increases, so the voltage across *R* decreases. Whatever the voltage across *T* may be, this same amount of voltage must appear also at *V*, or the temperature-instrument motor *M* moves slider 2 on *S* until *V* becomes equal to the *T* voltage. When the *V* and *T* voltages are equal, no voltage remains between slider 2 (on *S*) and point 1; therefore, no signal appears at *F*, the input to the amplifier.

21-6. The Bailey Pyrotron Amplifier.—This temperature-recording-instrument circuit is outlined in Fig. 21*E*. Using resistance *T* to respond to the furnace heat, this circuit amplifies whatever a-c signal is produced at *F*; as a result, motor *M* turns so as to move the slider on *S*, thereby decreasing this *F* signal. Power tubes *C* and *CC* supply direct current to saturable reactors 1*X* and 2*X*,[28-6] to control the motor.

The voltage-amplifier tubes *A* and *AA* in Fig. 21*E* are capacitor-coupled like those shown in Fig. 21*C*. When the potential at grid 5 rises rapidly, the grid-6 potential falls, but point 7 also rises. Notice that the large signal at 7 (grid of triodes *C* and *CC*) changes in the same direction as the small input signal at *F*.

The anodes of triodes *C* and *CC* receive voltage from opposite ends of transformer winding *T* (like the similar tubes in Fig. 21*C*). If grid 7 is positive during the half cycle when the *T* winding is also positive at 12, electrons flow from mid-point 2, through triode *C* to 11, through the d-c winding of saturable reactor 1*X*, to 12. However, if grid 7 is not positive until a half cycle later, electrons flow instead through triode *CC* and saturable reactor 2*X* to 14. If there is no input signal *F* and no voltage across 8*R*, the grid voltage of triodes *C* and *CC* is zero, and they pass current

in turn. Reactors $1X$ and $2X$ then receive the same amount of d.c. through the tube anodes, so that the same amount of alternating current may pass through each reactor. The voltage of the a-c-supply-autotransformer winding (8 to 9), forces current to flow back and forth between junction 15 and junction 18; half of this current flows through the a-c winding of reactor $1X$ and the J winding of the motor. An equal current flows through $2X$ and the K motor winding. There is no voltage between

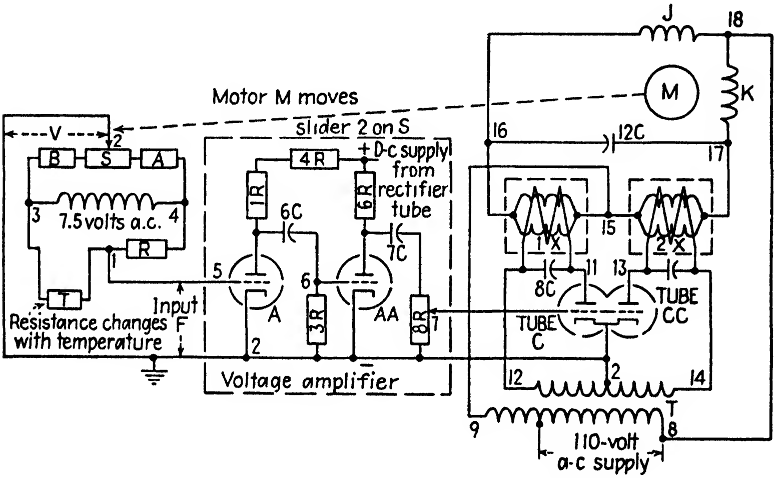


FIG. 21*E*. Circuit of Bailey Pyrotron Amplifier.

points 16 and 17 so capacitor $12C$ has no action. Since the currents in the two motor windings are in phase with each other, this a-c motor does not turn.

Now watch the circuit action when the furnace temperature rises, increasing the T resistance and the voltage across T. A small a-c voltage now appears between slider 2 and point 1; this voltage at F makes grid 5 positive during the same half cycle when T terminal 12 is positive; grid 7 is also positive at this time, so triode C passes current,* which saturates reactor $1X$. During the next half cycle, when 14 is positive, tube CC passes very little current, since its grid 7 is now negative.

With anode current flowing in tube C, but not flowing in tube CC, alternating current flows through reactor $1X$ but not through

* This tube current flows in pulses; capacitor $8C$ is charged during these pulses and keeps a more steady flow of d.c. through the reactor winding.

2X; as much as 120 volts a.c. appear between points 16 and 18. This voltage forces current to flow through motor winding *J*; current flows also through winding *K* in series with capacitor 12*C*. Because of 12*C*, the wave of alternating current through *K* is nearly 90 degrees ahead of the *J* current wave. Since the currents in these two windings are not in phase, the motor turns like a two-phase induction motor; it moves slider 2 toward the right on resistor *S* until voltage *V* becomes as large as the voltage across *T*. Then the motor stops.

For the opposite action, when the furnace cools and the voltage across *T* becomes less than *V*, a small a-c voltage again appears at *F*, but it drives grid 5 and grid 7 negative during the half cycle when 12 is positive. The tube-*C* anode current becomes small or zero, while tube *CC* passes current and saturates reactor 2*X*. With very little alternating current flowing through 1*X* but with more through 2*X*, as much as 120 volts a.c. now appears between points 17 and 18. Current flows through motor winding *K*; current flows also through winding *J* in series with capacitor 12*C*. The a-c wave through *J* is nearly 90 degrees ahead of the *K* current wave. The motor again turns (but in the direction opposite to that described above); it moves slider 2 toward the left on *S* until voltage *V* decreases and becomes equal to the voltage across *T*. Then the motor stops.

When voltage *V* is much larger or smaller than the *T* voltage, the *F* voltage is large; the large current in one motor winding lags farther behind the large current in the other motor winding, so the motor turns at high speed. When voltages *V* and *T* are nearly equal, the motor currents are small and are more nearly in phase, so the motor turns very slowly.

Questions

True or false? Explain why.

1. The cathodes of two capacitor-coupled tubes may be at the same potential.

2. In Fig. 21*C*, if the size of 2*C* or 4*C* is reduced, the circuit can respond to slower signal changes.

3. In Fig. 21*C*, if 2*C* is shorted, the grid of tube *AA* can never be negative.

4. In Fig. 21*C*, if capacitor 4*C* is shorted, tube *B* passes steady direct current.

5. In Fig. 21*C*, if 4*C* is shorted, tube *C* passes steady direct current.

6. In Fig. 21*C*, if 11*R* is shorted, the anode current of tubes *C* and *CC* increases.

7. In Fig. 21*C*, if 10*R* is shorted, the motor turns faster.

8. In Fig. 21*D*, an a-c voltmeter connected between *A* and *B* can show which slider is farthest to the left.

9. In Fig. 21*E*, if 12*C* is shorted, motor *M* will not turn.

10. In Fig. 21*E*, if thyratrons replace tubes *C* and *CC*, the motor runs at full speed or not at all.

11. In Fig. 21*E*, if you double the anode current of tube *A*, the voltage across 3*R* decreases.

CHAPTER 22

HIGH-SPEED LIGHT RELAYS

There are many applications that require high-speed photoelectric relays that can be operated by very rapid changes in light, lasting perhaps one-thousandth of a second.

22-1. Speed Limit of A-c Operation.—Let us analyze an example and see why a high-speed photoelectric relay is required and why a phototube used in an alternating-current circuit cannot be used for high-speed operation. Suppose that a bar of soft metal comes out of a forming machine at a rate of 5 feet per second (60 inches per second) and is to be cut into 5-foot lengths

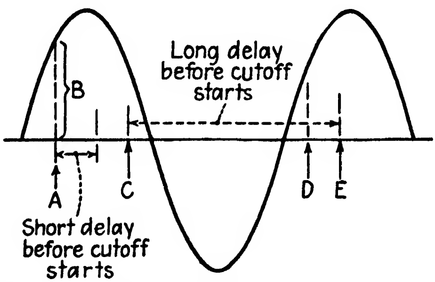


FIG. 22A.—With a-c supply, variable delay prevents accurate response.

with an accuracy of 1/8 inch. The bar moves along a conveyor, under the cutter and to a photoelectric relay 5 feet from the cutter. When the bar breaks the narrow beam of light between the light source and the photoelectric relay, the cutter operates. Can we obtain the desired accuracy if the cutoff is operated by an a-c solenoid and controlled by the fastest a-c photoelectric relay, which responds in 1/20 to 1/60 of a second? Since the bar moves 60 inches a second, it moves 1 inch in 1/60 second. This indicates the nearest accuracy that might be obtained is 1 inch, which is far from the 1/8-inch accuracy required.

Before we discuss the use of a high-speed relay, let us see why we cannot obtain high-speed operation as long as we supply alternating current directly to the tubes and the solenoids. Figure 22A shows 1½ cycles of voltage from a 60-cycle supply source.

If the beam of light is broken at the instant shown at point A, there is enough voltage available (B) at that part of the sine wave to start the cutoff operation almost instantly. However, if the light beam is broken at point C, there is too little supply voltage until point D, so the cutoff may not start until perhaps at E. During this longer delay the metal bar moves an extra quarter or half inch, which is outside the desired accuracy of 1/8-inch cutoff.

22-2. Fast Relay Response (CR7505-J5).—The light-operated relay of Fig. 22B gives great accuracy at high speed. While this circuit uses power from a single-phase a-c line, it first changes part of this a.c. into d.c. for internal use. Rectifier tube 1 with its filter[10-4] (2C, X, 3C) produces d-c voltage between points 1 and 3, so that tube 4 may pick up relay A at any instant.

This type of relay may control cutoff knives and package-wrapping machines, where the phototube 3 "sees" a narrow mark printed on the wrapping paper passing by. Perhaps this mark changes the light (reaching phototube 3) for less than 1/1000 second.

The central part of Fig. 22B is shown again in Fig. 22C, simplified. When amplifier tube 2 passes anode current, these electrons flow from point 4 of the voltage divider (4R, 5R, 6R), cathode to anode of tube 2, through 3R and the milliammeter to point 1. Of course, the amount of this flow depends on the tube-2 control grid, which is at the potential of point B, somewhere between points 4 and 3 on the voltage divider.

If much light shines on phototube 3, it permits electrons to flow from point 3, through 1R and the phototube to point 2. This flow causes so much voltage drop across 1R that the potential at B (grid of tube 2) is raised above point 3 and close to point 4, the cathode of tube 2. This causes tube 2 to pass current, which is shown by the milliammeter, MA. Notice that, if the light on phototube 3 remains constant so that the grid potential at B does not change, we can still adjust the amount of current in tube 2 by moving the slider of 4R. If 4R is turned clockwise, this raises the cathode-4 potential and reduces the tube-2 current. (4R is usually set so that tube 2 passes about 1 ma while phototube 3 receives light.) While tube 2 is passing about 1 milliampere, this current causes a large voltage drop across 3R, so that point 6 is at a potential far below point 1.

If phototube 3 is now darkened, the current decreases through 1*R* and the phototube. This reduces the voltage drop across 1*R* so that point *B* drops closer to point 3. This lowering of the grid potential of tube 2 decreases the amount of current flowing

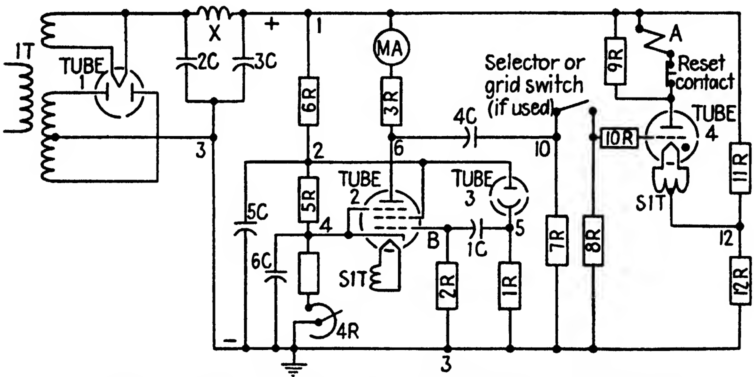


FIG. 22*B*.—Circuit of high-speed photoelectric relay (CR7507-J5).

through tube 2 and 3*R*. This reduces the voltage drop across 3*R*, so that the potential of point 6 rises. When a dark spot passes and darkens the phototube, the resulting dip in tube-2 current causes the potential of point 6 to rise; this rise may be applied to the grid of thyratron 4 to make it fire.

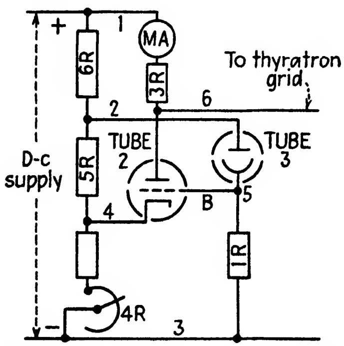


FIG. 22*C*.—Portion of Fig. 22*B*, simplified.

In Fig. 22*C* note that a slow decrease of light causes a slow decrease of tube-2 current and a slow rise of potential at point 6; as long as phototube 3 remains dark, point 6 remains at a raised potential. This action can give trouble, since such a circuit responds not only to the dark spot on the paper, but also to any gradual change in the light reflected from the rest of the paper. This high-speed relay will give more positive or definite action if we change its circuit so that it responds only to *sudden* changes of light, so it is not affected by slow light changes caused by dirt gathering on the

lens or phototube, or by the use of a roll of darker paper. The relay of Fig. 22*B* responds only to sudden changes of light, so let us see how we change Fig. 22*C* to get this action.

22-3. Response Only to Sudden Light Changes.—In Fig. 22*B* we have added 1*C* and 2*R* in the tube-2 grid circuit. (By the addition of capacitors 1*C* and 3*C*, these tube circuits become "capacitor-coupled.")[21-3] Now let us see how this circuit behaves.

When a constant or steady light falls on phototube 3 in Fig. 22*B*, the phototube current causes a voltage drop across 1*R* (the same as in Fig. 22*C*). However, notice that capacitor 1*C* is charged to this same voltage (the drop across 1*R*). Current flows through 2*R* only while 1*C* is charging or discharging. While the voltage across 1*R* is steady, there is no voltage drop across 2*R*, so the tube-2 grid *B* is at the same potential as point 3. By moving 4*R* slider upward, we lower the tube-2 cathode potential and thereby increase the current flow through tube 2 to the desired steady amount of about 1 ma.

If the amount of light on phototube 3 now slowly decreases, the current decreases through phototube 3 and 1*R*, slowly reducing the voltage drop across 1*R*. However, while this voltage across 1*R* slowly decreases, 1*C* discharges to this reduced voltage by forcing a very small current to flow through 2*R*. During this process, the tube-2 grid at *B* is not affected much. No matter how much or how little light shines steadily on phototube 3, capacitor 1*C* has charged to the voltage across 1*R*, and *B* is still at the same potential as point 3; the tube-2 current is unchanged from its steady value of 1 ma and there is no change in the potential at point 6.

If a printed mark passes, suddenly reducing the amount of light reaching phototube 3, the current through phototube 3 and 1*R* decreases sharply, and suddenly reduces the voltage drop across 1*R*. This is shown in Fig. 22*D*, where the potential at point 5 suddenly decreases from *K* to *L*. Capacitor 1*C* cannot discharge through 2*R* fast enough to follow this abrupt change of voltage across 1*R*, so point *B* is forced more negative than point 3. This action forces the tube-2 grid more negative, making the dip in tube-2 current shown at *N*. The resulting reduced voltage across 3*R* makes the point-6 potential rise suddenly (shown at *P*), which trips thyratron tube 4, as explained below.

The resistance of $2R$ is so high that little of the charge and voltage of $1C$ is lost while the printed mark passes.

22-4. Sudden Tripping of Thyratron.—In Fig. 22*B* the grid of thyratron tube 4 is connected* through capacitor $4C$ to point 6, and also through $7R$ to point 3. The action of point 10 may be

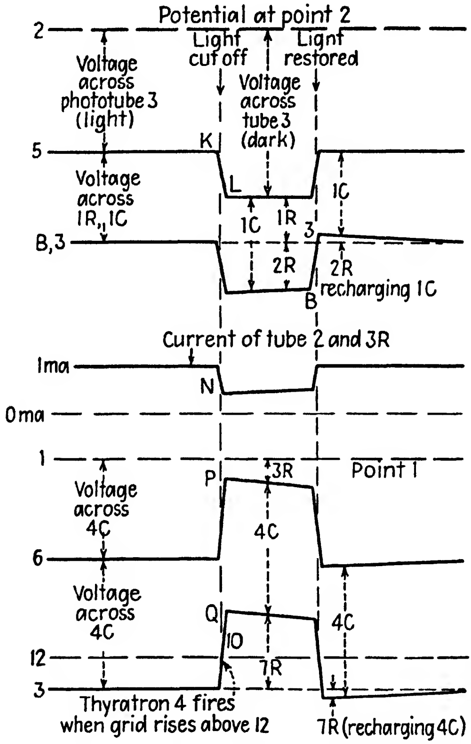


FIG. 22*D*.—Changes of voltage and current when phototube is suddenly darkened.

compared to that of point *B* above. With constant light on phototube 3, $4C$ is charged to the voltage between points 6 and 3, so the tube-4 grid is at the negative potential of point 3. Notice that the cathode of thyratron tube 4 is connected to point 12 on a voltage divider, so the tube-4 grid is now more negative than the cathode, by the amount of the voltage across $12R$; this nega-

* Sometimes a selector switch is used (as shown in Fig. 22*B*), when this light relay is used with web-register controls (see Chap. 23). The register machine drives the shaft of the selector switch to open the selector contact during times when the thyratron 4 need not be tripped.

tive grid bias prevents the firing of tube 4. If the potential at 6 is raised slowly (as when $4R$ is adjusted to decrease the amount of tube-2 current), capacitor $4C$ charges to this increased voltage without affecting tube 4 much.

When the point-6 potential rises suddenly (at P in Fig. $22D$), the voltage across $4C$ cannot change this quickly, so the potential at 10 (grid of tube 4) also rises abruptly as shown at Q. This rise in grid voltage trips or fires tube 4, whose anode current energizes or picks up relay A. Remember that tube 4 and relay A operate on direct current; even though the thyratron grid again becomes negative after a very short time, this vapor-filled thyratron tube 4 has been fired and continues to pass current. Relay A remains energized until the "reset contact" is opened, as by some part of the wrapping machine.

The impulse that trips the thyratron may last only 1/10,000 of a second. How fortunate that this vapor-filled type of tube, when once tripped by such a flicker, continues to pass current until the desired relay action takes place.

22-5. General-purpose High-speed Light Relay (CR7505-N110).—Although this relay includes no thyratron tube, the circuit of Fig. $22E$ acts suddenly even when the light changes slowly; its relay CR may be picked up by a light change as short as $\frac{1}{1000}$ second.

There are two separate d-c supplies; the left-hand part of tube 1 rectifies the a-c voltage of transformer $1T$ so that d-c voltage appears between points 1 and 5 (filtered by $3C$) to operate tubes 2 and 3. The other part of tube 1 furnishes d.c. between points 10 and 7; part of this is filtered by $4C$, $21R$ and $2C$, to operate tube 4 and relay CR.

As connected in Fig. $22E$, relay CR picks up when the light decreases* on phototube 2. With strong light on tube 2, enough current flows through $1R$ so that point 3 (grid of tube 3) is near the same potential as cathode 4; tube 3 passes anode current. These electrons flow from point 7 though $2R$ to 4, through tube 3 and $3R$ to point 1. This flow causes little voltage drop across

* There is a switch (not shown in Fig. $22E$) that can reconnect the tube-2 circuit so that CR picks up when the light *increases*. A capacitor may be added to couple tube 2 to tube 3, so that the relay responds only to quick changes of light. Figure $22E$ omits many parts of voltage dividers used in the complete relay.

$2R$ (about 50 ohms), but causes large voltage drop across $3R$ (0.1 megohm) so that point 2 is not far above cathode 4. Grid 6 is far more negative than cathode 4, so tube 4 is not passing current; relay CR is not picked up.

When the light reaching phototube 2 decreases slowly, it may have no effect on tube 4 or relay CR at first; during such a change, the tube-3 current slowly decreases. Point 2 slowly rises, raising the grid-6 potential; however, grid 6 is still below or near cutoff of tube 4, so the tube-4 current has not started to flow.

When the light has decreased just the right amount, the circuit suddenly trips;* the tube-4 current increases quickly and picks up relay CR. Let us see what causes this sudden change.

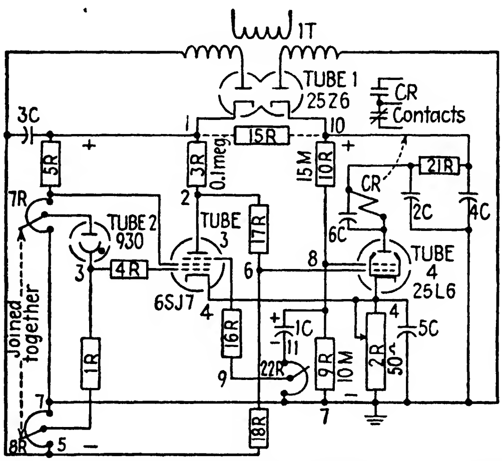


FIG. 22E.—General-purpose high-speed light relay (CR7505-N110).

22-6. Quick-tripping Action.—At this tripping point, grid 3 (of tube 3 in Fig. 22E) is lowered enough so that tube 3 is partly turned off; point 2 has risen enough to let grid 6 start the flow of anode current through tube 4. These electrons flow from point 7 through $2R$, tube 4, relay coil CR and $21R$ to point 10. This is a low-resistance circuit, and the anode current in beam power[7-10] tube 4 may become 30 times greater than the largest tube-3 current. As this larger tube-4 current starts to flow through resistor

* The desired tripping point is selected by dials $7R$ and $8R$, which always turn together. (The voltage between these two sliders is kept less than 90 volts at any setting, to protect the phototube.) When set higher (clockwise), the light on phototube 2 must drop to a lower amount before relay CR can operate.

$2R$, a voltage appears across $2R$ that makes cathode 4 more positive. As cathode 4 of tube 3 rises, it turns off tube 3 further; instantly this raises points 2 and 6 further, turning tube 4 on more and producing greater voltage across $2R$. Even if the potential of grid 3 has not changed since this action started, the tube-3 cathode is raised quickly by the increasing voltage across $2R$, so that the tube-3 current suddenly stops. Points 2 and 6 rise quickly and tube 4 passes large current at once, picking up relay CR. Notice that the tube-4 current cannot stay at any middle value; when it once starts to flow, the circuit quickly increases the tube-4 current to full amount.

When light again increases on phototube 2, this may raise grid 3 and lower points 2 and 6 somewhat, without decreasing the tube-4 current. However, when the tube-4 current starts to decrease, the voltage across $2R$ also decreases; cathode 4 drops and causes more current in tube 3 (even though grid 3 may not have risen further). As this increased tube-3 current lowers points 2 and 6, tube 4 is turned off more and the voltage across $2R$ decreases further, lowering cathode 4 more. This chain of events quickly stops all current through tube 4, so relay CR drops out at once.*

22-7. Action on Very Short Light Dips.—While the circuit of Fig. 22E trips suddenly, even when the light changes slowly, tube 4 may be turned on and off by sudden changes of light. However, if the light is stopped for only $1/1000$ sec, tube-4 current flows for so short a time that it cannot pick up relay CR. However, Fig. 22E includes a "pulse-lengthening" circuit, so that tube 4 can pass current for as long as $1/2$ sec and pick up relay CR, even though phototube 2 "sees" only a $1/1000$-sec dip in light.

Here let us study the circuits that furnish voltage to the other grids of tubes 3 and 4. The tube-3 suppressor grid at point 9 is connected to a slider on $22R$; when the slider is touching at point 7, this suppressor-grid potential does not change, so the action of tube 4 is as fast as the light change at tube 2. Now turn the $22R$ slider toward $1C$; whatever voltage appears across $22R$ now changes the tube-3 suppressor-grid voltage. Notice that $22R$ and

* In Fig. 22E, tube 3 is off when tube 4 is passing current. The tube-4 current is large enough to draw point 10 to a potential lower than point 1; current flows through $15R$, and both halves of tube 1 supply this tube-4 current.

1*C* are connected across 9*R*; 9*R* and 10*R* divide the d-c voltage (between points 10 and 7), so that screen grid 8 is about 40 volts more positive than cathode 4. While the lighted phototube 2 keeps tube 3 passing current, control grid 6 is negative; grid 6 not only prevents anode current from flowing in tube 4—it also prevents electron flow from cathode to screen grid 8. The voltage across 9*R* is quite large, and capacitor 1*C* is charged to this voltage.

When the light decreases, raising the point-6 (control-grid) potential, electrons flow cathode to anode in tube 4 and flow also from cathode 4 to screen grid 8 and through 10*R* to point 10. This screen-grid current increases the voltage drop across 10*R*, so that the potential at 8 quickly drops as much as 40 volts. The voltage across 9*R* decreases 40 volts; capacitor 1*C*, discharging to reach this lower voltage, forces current through 22*R* so that point 11 is driven 40 volts below (more negative than) point 7. This voltage across 22*R* forces suppressor grid 9 of tube 3 so far negative that tube 3 cannot pass current. Even though the light dip at phototube 2 has passed and grid 3 is back up to normal, the negative grid 9 prevents current flow in tube 3 until capacitor 1*C* has had time to discharge. The time constant of 1*C* and 22*R* is $\frac{1}{4}$ second, so the voltage across 22*R* lasts long enough to keep tube 3 from passing current for as much as $\frac{1}{2}$ sec. Meanwhile, tube 4 passes current during this $\frac{1}{2}$ sec, which is long enough to pick up relay *CR*. *CR* may be arranged to close a circuit to keep itself picked up until released by some other device.

22-8. The Pinhole Detector.—Another high-speed photoelectric device is used to "see" holes as small as $\frac{1}{70}$ inch across, in a strip of tinplate steel moving past at high speed (50 to 900 ft per minute). This steel is used in making tin cans, so any portion containing a hole must be marked or rejected. To do this, an intense beam of light shines down on the moving steel strip, while a row of phototubes below the strip stands guard ready to catch the short flash of light through any hole—a flash that may last only $\frac{1}{1000}$ sec. Each light source and phototube watches a 2 inch width of moving tinplate, so as many as 24 phototubes are needed for use with strips up to 48 inches wide; these phototubes are connected in parallel, so that any one phototube works the marker when a hole passes.

Figure 22*F* shows the entire circuit of this pinhole detector;

the left-hand portion (tubes 1, 2, 3, 4 and 9) is like Fig. 22*A* above, and thyratron tube 4 is fired each time that a hole in the tinplate passes. Tubes 5 to 8 control the marker, as will be described later. This marker is a rough or knurled roller (not shown), which usually is kept from turning by a solenoid *B* (upper right in Fig. 22*F*). When it is so held, a flat part on the roller is nearest the moving strip, so the roller does not touch the tinplate.

When a hole passes above a phototube, the tube-8 current is decreased to let the solenoid-*B* plunger drop down. This starts the roller turning so that its knurled teeth bite into the tinplate near the edge of the strip, leaving a mark 3 in. long. The moving strip now keeps the roller turning. After one complete turn, a cam on the roller raises the solenoid-*B* plunger. By this time, current again flows through tube 8 and the solenoid. Solenoid *B* is not strong enough to pull up its own plunger, but it will hold the plunger after it is raised by the roller cam. This locks the roller, to prevent further turning, until the next hole signal is received.

This marking roller is located 10 to 20 inches past the phototubes; a hole in the tinplate moves this distance before it can be marked. The pinhole detector includes a time delay (after the hole is "seen") so that the strip may move the right distance before the roller marks it. This timing is done by the circuit below tube 6.

Before studying the step-by-step action in Fig. 22*F*, let us dispose of many parts that merely hold steady voltages at certain points. Tube 9 with its pi filter[10-5] (*X* and 11*C*) supplies d-c voltage between top point 9 and bottom point 3. This voltage is split into useful parts (at the left) by 31*R*, 8*R*, 9*R* and 12*R*, while 19*C* and 13*C* help to hold steady voltage between 4 and 3. Tubes 2 and 3 are pentodes.[7-9] The potential at screen grid 38 is lower than point 37, because of electrons passing from cathode 35 to 38 and through 5*R*; 2*C* holds the screen-grid voltage constant. Similarly, the tube-3 screen is fed through 7*R* and 6*C*. Capacitors 3*C* and 5*C* brace the anode voltages at 37 and 29. Near the center of Fig. 22*F*, a voltage divider (18*R*, 27*R* and 15*R*) gives cathode potentials for tubes 4 and 7. Beam power tubes 5 and 8 get their screen potentials through 22*R* and 35*R*.

22-9. Response to a Pinhole.—All the phototubes are connected between points 31 and 33; only two are shown in Fig. 22*F*.

When no light reaches any phototube, very little current flows through resistor $1R$, so the tube-2 grid 33 is nearly down to point-3 potential. A small electron flow passes steadily from 3 through $2R$ and tube 2, through $3R$ and $4R$ to point 4; a small voltage appears across $2R$ as a bias to keep grid 33 slightly below cathode 35. Tubes 2, 3 and 4 are capacitor coupled[21-3] through $4C$ and $7C$. With no signal from a phototube, tube 3 passes a steady current* which, flowing through $11R$, makes the point-5 potential about 120 volts lower than point 29. Tube 4 is not firing, for its grid is now at point-3 potential, about 16 volts below the tube-4 cathode at point 27. Although the A contact above tube 4 is closed, no current flows to pick up contactor E; the potential at point 24 is the same as that at 9. Meanwhile, the control grid 28 of tube 5 is at cathode potential 3, so tube 5 has a large anode current; these electrons flow from 3 through tube 5, $24R$, through the pilot generator, $36R$, $37R$ and tube 6 to point 22. Because of this tube-5 current, the voltage between points 40 and 3 is small, so $12C$ has little charge. Point 7 (grid of tube 7) has much lower potential than cathode 44, so no current flows through tube 7 and $26R$. Tubes 7 and 8 are capacitor coupled through $10C$. With no signal from phototube 1, grid 47 is at point-3 potential, so tube 8 passes current and solenoids A and B are both picked up.

When a hole in the tinplate lets light flash onto a phototube, current flows through that phototube and $1R$. The potential of grid 33 rises and turns on tube 2. Point 36 falls suddenly, so $4C$ pushes grid 60 negative, turning off tube 3. The potential at 5 rises suddenly, so $7C$ raises the potential along $14R$, so that grid 32 rises and fires thyratron tube 4. (When the slider of $14R$ is at its upper end, tube 4 is fired by very small pinholes; at lower $14R$ settings, only the larger holes can fire tube 4.) The large current through tube 4 picks up contactor E, whose contacts (not shown) light signal lamps and operate a counter or a separate device to open a "gate," which diverts the bad piece†

* The grid 60 of tube 3 is held 1.25 volts below cathode 3, by a bias cell. This cuplike device is like a small dry cell or battery. Since it supplies no current it has very long life. Several bias cells together may give a larger voltage, like those below tube 6 in Fig. 22F.

† The strip of tinplate is cut into lengths just after passing the phototubes; these cut pieces then pass the "gate."

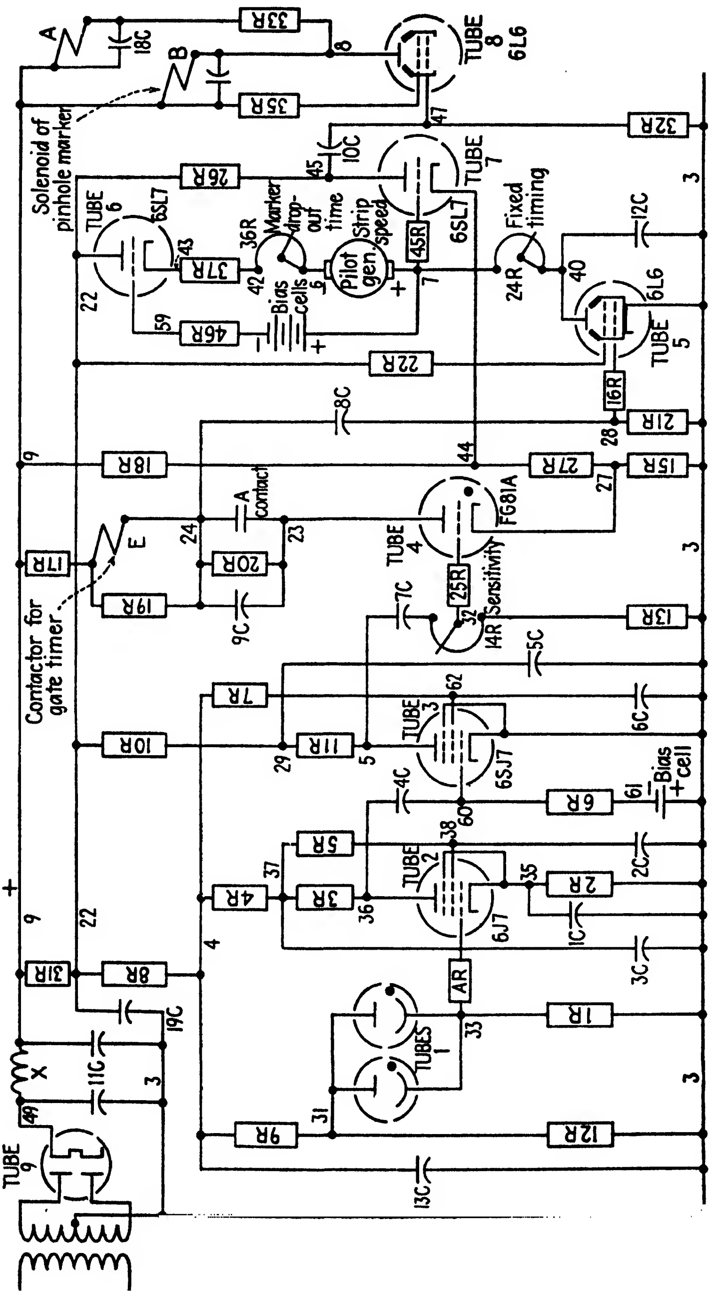


FIG. 22F.—Pinhole detector (CR7505-F121).

of tinplate onto a "reject" pile. When tube-4 current flows through E and $17R$ (top center of Fig. $22F$), the potential at point 24 drops; capacitor $8C$ forces grid 28 far negative, stopping all current through tube 5. At once the voltage across $12C$ starts to rise as current flows through $24R$ and tube 6 to charge $12C$.

The purpose of the tube-6 circuit (including the pilot generator, $36R$, $37R$ and grid-bias cell) is to control the current that charges $12C$, so that the grid potential 7 rises at a constant rate, as will be explained later. This charging of $12C$ gives a short time delay after which grid 7 turns on tube 7; this tube-7 current through $26R$ decreases the potential at 45 and grid 47, stopping the anode current of tube 8. Solenoid B quickly releases its plunger, to start the marking roller. Relay A is held in a bit longer (until $18C$ loses its charge) to give the B plunger time to drop all the way down. Then A opens its contact (center of Fig. $22F$), which removes anode voltage from thyratron 4. (By now the impulse from the phototube has passed, so grid 32 is back at point-3 potential.) Since current stops in $17R$ and E, the point-24 potential returns to point 9; $8C$ brings grid 28 up so that tube 5 again passes current, discharging $12C$ and lowering the grid-7 potential. Tube 7 turns off and tube 8 turns on, picking up relay A; voltage returns across solenoid B to let it hold its plunger after the marking roller has turned. This whole chain of events takes place in part of a second; it resets tube 4 ready for the next phototube signal.*

22-10. Time Delay for Marker.—If the tinplate strip moved always at the same speed, a simple time-delay relay could mark the strip at the right spot, by releasing the marking roller at a fixed time after the hole was "seen." However, this machine must be able to mark the right spot, whether the strip is moving

* Above tube 4, see how $20R$ and $9C$ can prevent tube 4 from firing again when contact A closes. Without $20R$ and $9C$, anode 23 remains at low potential when contact A opens; since point 24 rises, several hundred volts appear across the A contact. When A recloses, anode 23 suddenly rises this amount; through the anode-to-grid capacity within tube 4, this thyratron grid also receives a voltage rise large enough to trip tube 4 again. However, with $20R$ and $9C$ added, the opening of contact A instantly charges $9C$ to the several hundred volts across the contact; as this charge then leaks off through $20R$, the potential of anode 23 rises more slowly and does not produce a false tripping signal at the tube-4 grid. By the time contact A recloses, anode 23 is already at a potential close to point 24.

50 ft. or 900 ft. per minute. At the 900-ft speed, the roller must mark the strip much sooner than at lower strip speeds; a circuit is needed that decreases its time delay to match exactly any increase in strip speed.

In the circuit below tube 6 in Fig. 22*F*, the pilot generator (or tachometer[28-1]) is driven by the rolls that move the tinplate; the d-c voltage of this generator increases just as fast as the strip speed, and "tells" the time-delay circuit how fast the strip is moving. This pilot-generator voltage is used in the grid circuit of tube 6. When the strip moves slowly, this 6-to-7 voltage is small, or less than the steady voltage of the bias cells that keep the tube-6 grid negative. At this low strip speed, tube 6 passes little current; these electrons charge capacitor 12*C* (after a pinhole turns off tube 5) by flowing through 24*R*, the pilot generator, 36*R*, 37*R* and tube 6. The voltage across 12*C* increases so slowly that the tinplate may move for several seconds before tube 7 passes current and tube 8 drops out the marker solenoid *B*.

However, when the strip is moving faster, the pilot generator produces more d-c voltage,* making point 7 more positive. This more nearly offsets the bias-cell voltage so that tube 6 passes greater current,† which charges capacitor 12*C* in less time; tubes 7 and 8 work sooner, so solenoid *B* lets the roller mark the strip sooner, which it must do to mark at the right spot.

Resistors 36*R* and 37*R* help tube 6 to pass constant current during the entire charging of 12*C*. Since tube 6 is a triode, its anode current tries to decrease if its anode voltage (22-to-43) decreases. Notice that, when 12*C* begins to charge, the 40-to-3 voltage is small, so the tube-6 anode voltage is large; when the 12*C* voltage has become greater, the tube-6 anode voltage is less, so tube 6 tries to pass less current. However, such a decrease of current also lowers the voltage drop across 36*R* and 37*R* and lets point 6 rise closer to cathode 43; this raises the potential of grid 59. Therefore, although the anode voltage decreases (to decrease the tube-6 current), the grid voltage increases (to increase the tube-6 current). As a result, the tube-6 current stays nearly constant, so that 12*C* is charged at a steady rate; the

* At fastest strip speed, the pilot generator produces about 100 volts.

† This current increases the voltage drop across 36*R* and 37*R* almost as fast as the pilot-generator voltage increases, so that grid 59 remains more negative than cathode 43.

potential at grid 7 rises steadily, so that marker solenoid *B* drops out at a time that is changed only by the strip speed. If the marker is placed closer to the phototubes, the resistance of 36*R* should be decreased to make the marker act sooner.

22-11. Long-distance Light Relay (CR7505-B100).—It is hard to make a phototube respond in daytime to a signal from a light that is a quarter of a mile away, unless a special kind of light signal is used. At such a distance, the amount of light from a signal is much less than the daylight; a phototube "sees" only the total amount of light, so the weak signal is lost if it comes from

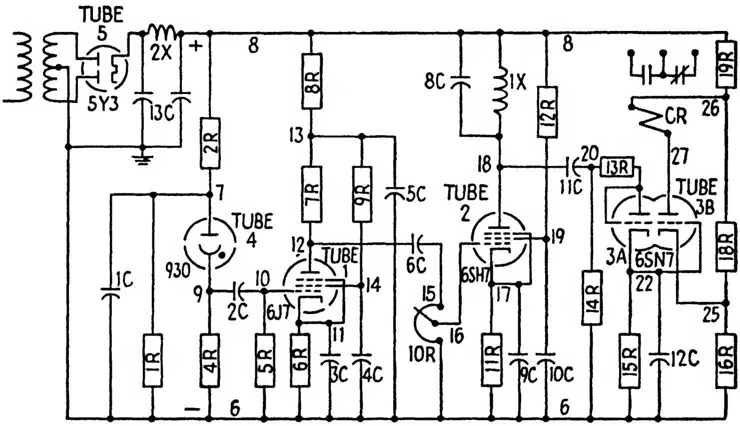


FIG. 22*G*.—Long-distance light relay (CR7505-B100).

a steady source of light. However, if the signal light has a beam that is chopped (turned on and off) about a thousand times per second, the light relay of Fig. 22*G* can "see" that flickering light but is "blind" to the steady daylight. A motor-driven shutter chops the light beam before it travels the long distance to the phototube; we say that the light beam is modulated, and Fig. 22*G* shows a modulated-light receiver. This circuit responds to the weak rays of moduated light but does not respond to the strong rays of steady daylight.

As long as the beam of modulated light shines on phototube 4 in Fig. 22*G*, relay *CR* (upper right) is picked up. If anything cuts that beam, day or night, *CR* drops out; the *CR* contacts may be used to give an alarm.

The a-c supply voltage (upper left in Fig. 22*G*) is rectified by tube 5 and filtered[10-4] by 2*X* and 13*C*, so that the rest of the circuit

operates from the d-c voltage between points 8 and 6. If phototube 4 receives only steady light or no light, the voltage across resistor $4R$ may be large or small; capacitor $2C$ becomes charged to this steady $4R$ voltage and grid 10 is at the potential of point 6. Tube 1 passes some steady current (and the voltage drop across $6R$ becomes the bias to keep grid 10 more negative than cathode 11). No matter what steady voltage exists between anode 12 and point 6, capacitor $6C$ becomes charged to this voltage; then grid 16 of tube 2 is at 6 potential. In the same way, no matter what voltage exists between tube-2 anode 18 and point 6, capacitor $11C$ holds all of this voltage; no voltage remains between points 20 and 6, so there can be no current in tube $3A$ or resistor $15R$. Grid 22 of tube $3B$ is at 6 potential, which is seen to be more negative than the tube-$3B$ cathode connected to point 25 on the voltage divider ($16R$, $18R$, $19R$); tube $3B$ passes no current and CR cannot pick up.

The circuit of Fig. $22G$ is designed to respond to a light beam that is modulated about 800 times per second. If some other light (flickering, say, 120 or 2000 times per second) shines on phototube 4, capacitor $2C$ and $6C$ may pass this signal to tube 2, yet tubes $3A$ and $3B$ do not respond. To learn why, notice the reactor $1X$ and capacitor $8C$, through which any tube-2 anode current must pass; $1X$ and $8C$ are of the right size to be resonant[20-8] at 800 cycles per second. If the tube-2 current changes only 120 times per second, this current passes easily through reactor $1X$; if the tube-2 current changes 2000 times per second, this current seems to pass easily through capacitor $8C$. In either case, there is very little voltage drop between points 8 and 18, so the potential at 18 does not rise or fall very much, although the tube-2 current changes.

22-12. The Modulated Light Works the Relay.—In Fig. $22G$, when the tube-2 current changes about 800 times per second (as when phototube 4 "sees" a light that flickers 800 times per second), this current cannot pass easily through either $1X$ or $8C$; the tube-2 current causes much greater voltage drop across them so that, as tube-2 rapidly turns off and on, the potential at point 18 rises and falls a large amount. These changes at point 18 make capacitor $11C$ charge and discharge. When the potential drops at point 18, capacitor $11C$ discharges and forces electrons to flow from point 20 through $14R$ to 6, through $11R$ and

tube 2 to point 18. However, when point 18 rises, capacitor 11*C* charges and draws electrons from negative point 6 through 15*R*, tube 3*A*, 13*R* to points 20 and 18, and through 1*X* to positive point 8. This charging current causes a voltage drop across resistor 15*R*; capacitor 12*C* becomes charged to this voltage. (Tube 3*A* acts only as a diode valve.) Notice that 12*C* becomes charged only while 11*C* is charging; while 11*C* discharges, 12*C* holds most of its own charge, since 15*R* has too great resistance to drain away much of the 12*C* voltage in so small a part of a second.

This charge in 12*C* forces point 22 more positive than point 6; when 12*C* is charged, grid 22 of tube 3*B* rises, so that current flows in tube 3*B* and the coil of *CR*. In this way, *CR* is picked up whenever the tube-2 current is changing about 800 times per second, for then point 18 rises and falls, "pumping" a charge into 12*C*, which turns on tube 3*B*. If the light beam is broken for even $1/100$ sec, 12*C* discharges through 15*R*, so that *CR* drops out.

Questions

True or false? Explain why.

1. In Fig. 22*B*, there is voltage across 8*R* whenever selector contact *X* is closed.

2. At any setting of 22*R* in Fig. 22*E*, relay *CR* may respond to slow changes of light at tube 2.

3. Screen-grid current flows whenever the screen is more positive than the cathode.

4. In Fig. 22*E*, tubes 2 and 3 are capacitor coupled.

5. In Fig. 22*E*, only one electrode of tube 3 has constant potential.

6. In Fig. 22*E*, if 2*R* or 5*C* is shorted, tube 3 cannot turn on tube 4.

7. In Fig. 22*F*, after the firing of tube 4 turns off tube 5, tube 5 passes current a little later even if contact *A* does not open.

8. In Fig. 22*G*, phototube 4 responds only to the changing light.

9. In Fig. 22*G*, if 8*C* and 1*X* are replaced by resistors, the whole circuit may respond to daylight.

10. In Fig. 22*G*, current flows in 9*R* only when 4*C* charges or discharges.

11. In Fig. 22*G*, capacitors 1*C*, 4*C*, 5*C* and 10*C* can be removed without changing the circuits' response to the light beam.

12. In Fig. 22*G*, the voltage across 16*R* is the grid bias of tube 3*B*.

CHAPTER 23

REGISTER CONTROLS

High-speed light relays (like those of Chap. 22 but having more circuits, as described below) may be used to control the printing or cutting of paper as it comes off large rolls.* This "web" of paper already has some marking; more printing or cutting is to be done so that the new design or cut will be made exactly in step with the earlier marking. At each instant when the moving paper web is in correct position, the web is "in register"—the new design or cut is made exactly right. Other light relays may keep strips of paper or metal in line, from side to side, so that they may be slit accurately or wound into rolls having smooth edges; these are side-register controls.

23-1. Two-way Register Control.—The equipment whose circuit is shown in Fig. 23*B* gives "two-way" correction; it can either move the web farther ahead or delay the web so that the printed design is kept in step with the wrapper or the cutoff knife.

This printed design is usually in sections and must be cut between these sections. With such a unit design, it costs less to print on a continuous web of paper than on separate precut sheets; it is hard to handle certain stocks (such as cellophane) unless web printing is used. Such web stock is printed and then wound on a roll, to be fed later into the packaging or bag-making machine; there is no definite "tie-in" between the timing of the printed design and the timing of the drive roll that feeds the web into the machine. Therefore, if the feed-roll travel (per machine revolution) differs slightly from the spacing of the printing on the web, the knife will soon cut into the printed design. Even though the error of each cut may be only 1/100 inch or 1/10 of 1 per cent, after cutting 500 sheets the cut will occur in the middle of the printed design rather than at the end—and it requires a very short time to make 500 cuts on a high-speed packaging machine.

* As examples, the printing of newspapers and magazines in several colors; high-speed paper-bag-making machines or package-wrapping machines using printed paper; the perforation of sheets of postage stamps.

It is hard to keep this register even by using the exact calculated gear ratio between the cutter and the feed roll; several things change, such as the slippage, the tension applied to the paper, and the stretch or shrinkage of the paper, caused by varying moisture conditions in the air. These changes may add up so that each successive cut is made with a greater error. To reduce these spoilages and produce a more uniform product and also to increase production by allowing higher machine speeds, the photoelectric web-register control is used.

A packaging or bag-making machine equipped for handling a printed web should, therefore, have a way to change the speed of the feed or draw roll, as compared to the speed of the turning knife that cuts the web. There must also be some way to tell whether the printed design is in exact register with the cutter. This can be done well by using a photoelectric tube to "see" the printing and to compare its relative position with that of the cutter.

With the aid of Fig. 23*A* let us see how a high-speed photoelectric relay is used with a mechanical arrangement to operate as a web-register or cutoff-register control. Paper from a large roll is fed into the wrapping and cutoff machine at high speed. The design already printed on the paper must be made to line up (usually within $\frac{1}{8}$ to $\frac{1}{64}$-inch) with the edge of the package or with the cutoff device; this is done by the photoelectric register control, while the printed web moves past. This photoelectric equipment, whose circuit is discussed later, must respond to a printed spot perhaps $\frac{1}{8}$-inch (measured in the direction of travel) by $\frac{1}{2}$-inch wide, moving past the "electric eye" (phototube) at speeds from 150 to 1000 ft per minute. To "see" this spot, which passes in approximately $\frac{1}{2000}$ sec, the photoelectric relay must be able to respond to these very rapid changes of light. Let us see how the phototube uses these rapid changes of light and makes the equipment give the necessary correction.

Figure 23*A* shows the paper with its printed register spots moving beneath the phototube and light source to the cutter, turning at constant speed. To this cutter is coupled a two-circuit rotary selector switch, which is closely lined up with the position of the cutter. Whenever the light is decreased at the phototube, an amplifier tube 2 gives a correction signal. To cause a correction, this signal must also pass through the selector

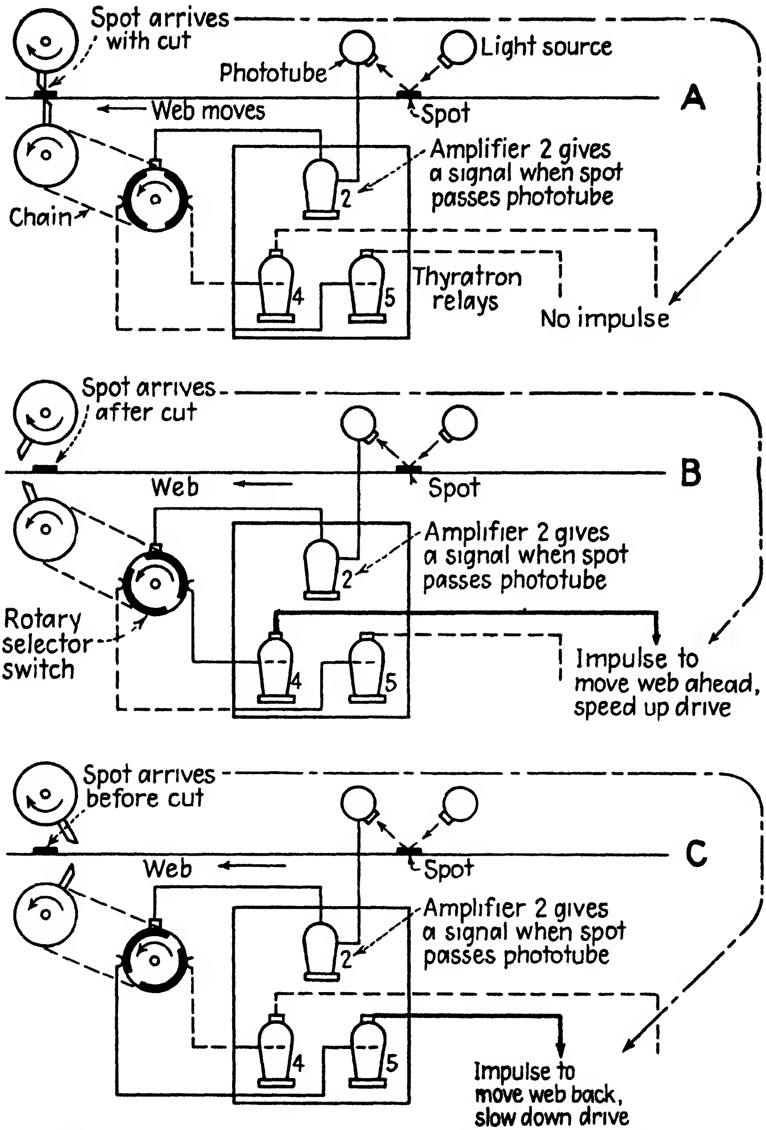


FIG. 23A.—Action of the phototube, selector switch and thyratrons in cutoff-register control.

switch, which has the choice of firing either one of two thyratrons. One thyratron relay increases the web speed for correction (by external circuits not shown) and the other thyratron relay decreases the web speed for correction.

In part *A* of Fig. 23*A* we see that neither correction is applied, for here the cutter is cutting the paper at the proper times and no correction is needed. Note that amplifier tube 2 still gives its signal but the rotary selector switch is in an open-circuit position and neither thyratron relay is energized. Part *B* shows the condition when the register spot arrives late at the cutter. Notice that the signal from tube 2 now passes through the selector switch so as to fire thyratron tube 4. This tube closes its relay, causing a correction that moves the web ahead and increases the speed of the feed roll. This correction continues until the spot and the cutter are in register and the conditions become like those shown in part *A*. Part *C* shows the conditions when the spot arrives before the cutter is ready. Here we see that the other thyratron 5 is fired, and its relay causes a correction that moves the web back and decreases the speed of the feed roll until the desired condition of part *A* is again obtained. Remember that the paper and the cutters and the selector switch are moving at high speed.

23-2. Cutoff-register Control (CR7505-W2A).—The complete circuit of this photoelectric register control is shown in Fig. 23*B*. This circuit includes several parts that we have already discussed. We find that this equipment furnishes its own direct current supply (upper left). The scanning head with phototube 3 and amplifier 2 is shown in the center. *TR* is an adjustable vacuum-tube time-delay relay (lower left) described in Sec. 6-7.

Most of Fig. 23*B* is the same as Fig. 22*B*;[22-2] the circuit now includes two thyratrons, 4 and 5.

Although every dark spot passing the phototube makes a "turn-on" impulse occur at point 10, the rotary selector switch decides whether this impulse is ever used to trip a thyratron. When both contacts (*X* and *Y*) are open, the grids of tubes 4 and 5 are at the negative potential at point 8. Contact *Y* is closed during the split second just before the dark spot is supposed to appear. If the spot appears early and produces the tripping impulse before contact *Y* opens, the "turn-on" impulse fires thyratron tube 5 and lets relay *R* give a retarding correction to the position of the printed web (by means of additional cir-

cuits not shown). If the spot appears exactly on time, contact Y has already opened and X has not yet closed, so neither tube fires or produces any correction. If the spot appears later, contact X has now closed, so the "turn-on" impulse reaches tube-4 grid; relay A gives a correction to the feed roll, which advances the spot toward the correct position.

The amount of each correction of the web depends on the length of time during which relay A or relay R remains closed; this, in turn, depends on time relay TR (lower left in Fig. 23B; see also Fig. 6H). Here we find tube 6 passing the current

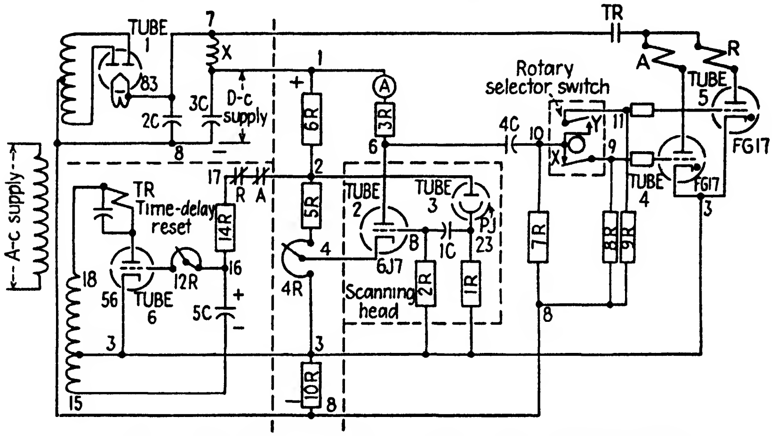


FIG. 23B Photoelectric-register-control circuit (CR7505-W2A).

necessary to energize TR so that its contact completes the circuit to relays A and R. This timer circuit of tube 6 differs from the usual electronic timer circuit, in that tube 6 is steadily passing current and contactor TR is picked up.

If the printed spot becomes out of register, so that a thyratron fires and picks up either relay A or R to start a correction, we see that one of the normally-closed contacts A or R opens; this disconnects 14R from point 2 and starts the time-delay action of TR.

When TR drops out, its contact removes anode voltage from thyratron tubes 4 and 5, and drops out contactor A or R, stopping the corrective action. The R and A contacts again connect the grid circuit of tube 6 to point 2, so tube 6 again picks up TR. However, during the short time when the TR contact was open, the grids of thyratrons 4 and 5 regained control, so that this tube circuit is reset to respond to the next corrective impulse.

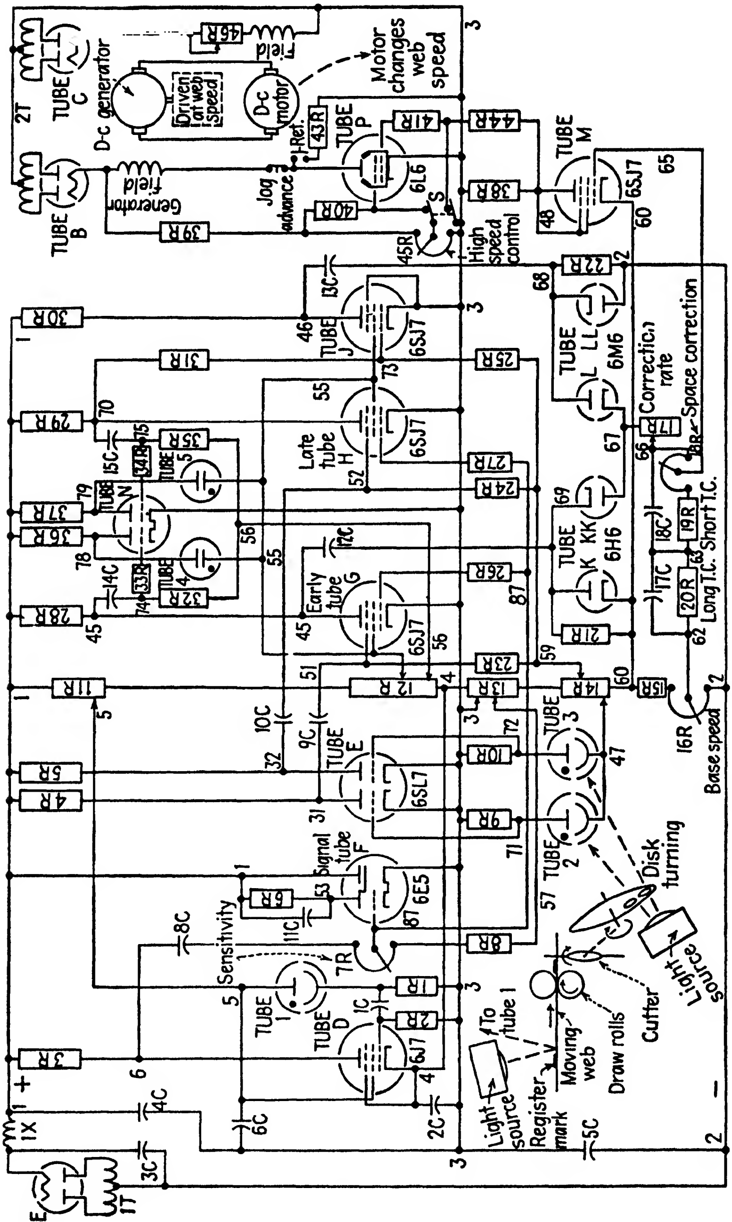


FIG. 23C.—Higher speed register control (CR7505-W110).

In addition to controlling the length of the correction applied to the printed web, this tube-6 circuit gives several protective advantages. Each time this equipment is placed in service, tube 6 prevents the closing of the anode circuit of thyratrons 4 and 5 until their cathodes are heated and ready to pass load current. Tube 6 has a slow-heating cathode, so it does not pass enough current to pick up *TR* until the thyratrons are hot.

If tube 6 fails, the circuit "fails safe," for the *TR* contact prevents the thyratrons from firing. If the failure of tube 6 permitted the thyratrons to fire, any corrective action might continue until the web became broken or the machine was damaged.

23-3. Higher Speed Web-register Control (CR7505-W110).—While this equipment controls web register in much the same way as that described above, the circuit of Fig. 23*C* includes extra tubes and features so as to work better at high web speeds. In place of a rotary-selector switch, the cutter turns a disk (lower left); holes in this disk are arranged so that light beams strike phototubes 2 and 3 before and after the register mark dips the light at phototube 1. Tubes *F*, 4 and 5 act as signal lights to help in adjusting the equipment. While Fig. 23*B* uses thyratrons to pick up relays for correction, Fig. 23*C* controls the field strength of a d-c generator (upper right) so that a d-c motor changes speed gradually, giving large or small corrections of the web speed as needed. This correction is made through differential gearing that can change the web speed by about 4 per cent. Unless the d-c correction motor turns, the web moves too fast; as the motor speed increases, the web speed decreases. At medium correction-motor speed, the web speed is just right.

The speed of the d-c correction motor rises when beam power tube *P* passes more current. Transformer 2*T* and rectifier tube *B* (upper right in Fig. 23*C*) make these electrons flow from point 3, through tube *P* and the generator field. More current in this field makes the generator give higher voltage, which runs the d-c motor at higher speed (for this motor's field is steady, supplied through rectifier *C* and adjusted by 46*R*). Notice how this motor speed is controlled by hand if switch *S* is closed; one *S* contact connects the control grid of tube *P* to point 3 (so that other tubes have no effect on tube *P*), and the upper *S* contact connects the screen grid to 45*R*. When 45*R* is turned clockwise, the screen potential rises and tube *P* passes more current, to retard the web.

All other tubes receive their d-c supplies from rectifier *A* (upper left); because of a filter[10-4] (3*C*, 1*X*, 4*C* and 5*C*), steady d.c. appears between points 1 and 3, and between 3 and 2. Briefly, phototube 1 controls tube *D* and the control grids of tubes *G* and *H*; phototubes 2 and 3 control the suppressor grids of tubes *G* and *H*. Tube *H* controls tube *J*. When either *G* or *J* passes current, tubes *K* or *L* (lower part of Fig. 23*C*) act as valves, so that capacitors 17*C* and 18*C* become charged; this controls tube *M*, which controls tube *P* and the correcting motor. Now let us study this in detail.

Phototube 1 and amplifier *D* are coupled through capacitor 1*C* as explained in Sec. 22-3. Each dark register mark on the web dips the grid voltage of tube *D*; its anode current decreases, so point 6 rises quickly and the potential rises at all parts of 7*R*. This raises the control grids 87 of tubes *F*, *G* and *H* (which had been at a negative potential at 13*R* slider). Therefore, each passing register mark makes tube *F* "wink" and tries to turn on tubes *G* and *H*.*

This "turn-on" impulse is shown at *A* in Fig. 23*D*; it will not turn on tubes *G* or *H* as long as the impulse occurs during "dead zone" *B*. During *B*, the suppressor grids of tubes *G* and *H* are both so negative that neither tube can fire, even when the control grids are positive. (This is like the action of the selector switch in Fig. 23*B*, when both contacts *X* and *Y* are open.)

The holes in the disk (driven by the cutter in Fig. 23*C*) are spaced so that no light reaches phototubes 2 or 3 during zone *B*. With no current through these phototubes, points 71 and 72

* Tube *F* is an electron-ray or indicator tube, which shows a circle of green light. The left-hand side of *F* (in Fig. 23*C*) is a triode amplifier. When grid 87 of this triode is too negative, no electrons flow from 3, cathode to anode 53, or through 6*R* to point 1; points 53 and 1 are at the same potential, so electrons flow freely from cathode to right-hand anode 1 of tube *F*. These electrons strike all parts of the anode circle, making a green glow over the entire circle. Notice the electrode or wire below circle anode 1, connected to anode 53 inside tube *F*. When a signal voltage raises the potential of grid 87, current flows through 6*R* so that point 53 becomes more negative than point 1; capacitor 11*C* charges to this voltage across 6*R*. Since the electrode is more negative than anode 1, it repels some of the electrons away from the circle; a dark wedge, or shadow, appears in the green circle. When grid 87 rises for an instant, the shadow wedge appears, then gradually closes again as 11*C* discharges through 6*R*; the "magic eye" seems to wink.

(grids of tube E) are at cathode potential 3, so tube E passes current through both $4R$ and $5R$; anode potentials 31 and 32 are low. Suppressor grids 51 and 52 are about 50 volts negative, near point 59 on $14R$.

Earlier than zone B, a disk hole lets light reach phototube 2; current through $9R$ lowers grid 71, turning off the left-hand triode of tube E. Anode 31 rises, and $9C$ raises the suppressor grid 51 also,* as shown during zone G of Fig. 23D. Also, later than zone B, a different disk hole lets light reach phototube 3; current through $10R$ lowers grid 72, so anode 32 rises and suppressor grid 52 becomes positive, during zone H. Neither of these actions turn on tube G or H, for the control grids are too negative to permit electrons to flow. As long as signal A from the register mark stays within zone B, tubes G and H give no correction signal.

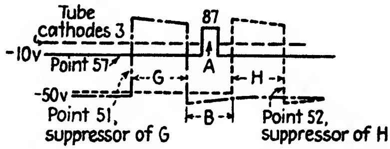


FIG. 23D.—Grid potentials in Fig. 23C, with spot in register.

23-4. Action to Slow the Web.—Suppose that the web is moving too fast, so that the register mark produces signal A too early, as is shown in Fig. 23E. At A the control grid becomes positive while the suppressor grid of tube G is still positive; with both grids positive, tube G passes current and electrons flow from point 3 through tube G to 45 and through $28R$ to point 1. The potential at point 45 drops (turning on glow tube 4[23-6]); capacitor $12C$, which was charged to the voltage between points 1 and 60, tries to discharge. Electrons flow from terminal 69 of $12C$, through tube KK and $17R$, into capacitors† $18C$ and $17C$, through $16R$, $15R$, $14R$, $13R$ to point 3, cathode to anode of tube G to point 45. These electrons charge $18C$ and $17C$ so that

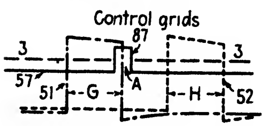


FIG. 23E.—Grid potentials, spot arriving early.

* The time constant[4-5] of $9C$ and $23R$ is about $\frac{1}{8}$ sec, so the voltage across $9C$ changes little during zone G.

† Although electrons may also pass through $18R$, $19R$ and $20R$, the discharge current of $12C$ changes so quickly that most electrons pass into $18C$ and $17C$. The voltage between points 66 and 62 is divided by the sizes of $18C$ (0.02 mu f) and $17C$ (4 mu f), instead of by the resistors. Most of the voltage appears across $18C$, little across $17C$. This path (from 69 through KK to 60) offers less resistance than the more direct path through $21R$.

point 66 becomes more negative than point 62. Notice that 62 is the grid potential of tube *M*, when there is no voltage across 18*C* and 17*C*. Grid 65 is driven more negative by part of this 66-to-62 voltage. So when 18*C* and 17*C* receive this discharge current from 12*C*, the tube-*M* anode current decreases through 38*R*. This raises the potential at 48 (control grid of tube *P*) so that tube *P* strengthens the generator field, raising the d-c motor speed which slows the web.

Each time a web-register mark arrives early, tube *G* passes a short impulse of current and discharges 12*C* into 18*C* and 17*C*. After the mark passes, the tube-*G* current stops, so 12*C* is recharged by electrons flowing from point 2 through 16*R*, 15*R*, and tube *K* to terminal 69, with a return flow from 45 through 28*R* to point 1. Tube *K* acts as a one-way valve around 21*R*, to let 12*C* recharge faster, to be ready for the next correction signal; meanwhile the rectifier, or valve, action of tube *KK* prevents 17*C* and 18*C* from discharging back into 12*C*.

23-5. Action to Speed the Web.—When the register mark arrives too late, impulse *A* makes the control grids of tubes *G* and *H* positive, while the suppressor grid of tube *H* is also positive. Current passes through tube *H* and 29*R*, so the potential at 70 drops; this lowers the control-grid voltage of tube *J* (and fires glow tube 5). As the current through tube *J* and 30*R* decreases, the potential of point 46 rises; while capacitor 13*C* charges to this increased voltage, electrons flow from point 2 and 16*R*-slider 62 into 17*C* and 18*C*, through 17*R* and tube *L* into 13*C*, with return flow from 46 through 30*R* to point 1. This electron flow charges 17*C* and 18*C* so that they become more positive at point 66; this makes grid 65 of tube *M* more positive than before, so tube *M* passes greater current. Grid 48 of tube *P* becomes more negative, so the generator field is weakened; the correction-motor speed decreases, thereby raising the web speed.

After the register mark passes, the tube-*H* current stops, so tube *J* again passes current; capacitor 13*C* discharges to a lower voltage by making electrons flow from point 68 through tube *LL* to 2, through 16*R*, 15*R*, 14*R* and 13*R* to point 3, and through tube *J* to point 46.

Let us study further the grouping of 17*C* across 20*R*, and 18*C* across 18*R* and 19*R*. Each time a late register mark fires tube *H*, the current that charges 13*C* also makes point 66 more positive

than point 62; most of this 66-to-62 voltage appears across 18*C* (see footnote above). Moreover, the time constant[4-5] of 18*C*, 18*R* and 19*R* is short (about 1/30 sec), so that this large voltage across 18*C* decreases rapidly; each single firing of tube *H* gives a large impulse to tube *M* and the correcting motor, so the motor speed rises sharply but then quickly returns to normal. At the same time, each firing of tube *H* places a small charge on capacitor 17*C*. The time constant of 17*C* and 20*R* is long (about 20 sec), so 17*C* holds its charge. Figure 23*F* shows how, when tube *H* fires several times, the voltage across 17*C* builds up and holds grid 65 more positive than 62 for a long time; this lowers the correction-motor speed for many seconds at a time. We see

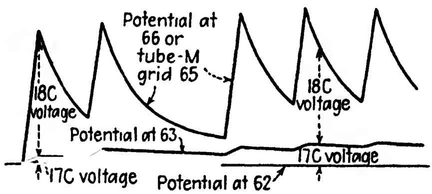


FIG. 23*F*.—Different time constants produce different web corrections.

that a voltage across 18*C* gives a sudden change of web position without much change of average web speed; this is space correction. However, voltage across 17*C* gradually increases the web speed when a large number of register marks appear too late; this changes the correction rate.

23-6. Light Signals Help Adjustment.—While the indicator tube *F* winks (see Sec. 23-3, footnote) each time a register mark causes the right change of light at phototube 1, tube 4 or tube 5 glows only when the mark is out of register, and a correction is given. As long as tube *G* and *H* do not fire, their anodes 45 and 70 are at the positive potential of point 1. Both grids of tube *N* (upper center of Fig. 23*C*) are at the potential of point 56 (a slider on 12*R*), which is more positive than *N* cathode 3. Both sides of tube *N* pass current; there is so much voltage drop across 36*R* and 37*R* that points 78 and 79 are near the potential of point 55. There is little voltage across tube 4 or tube 5; neither tube glows (for such vapor-filled glow lamps permit no current flow until the voltage across them is more than their arc voltage).

When an early register mark fires tube *G*, the point-45 potential drops; 14*C* forces grid 74 more negative than cathode 3 for

perhaps $\frac{1}{1000}$ sec. For this instant no current flows in the left-hand anode of tube *N* or in 36*R*, so voltage 78-to-55 increases; tube 4 glows—a brief flash to warn that a correction is given to slow the web. A late register mark fires tube *H* and lowers point 70; capacitor 15*C* forces grid 75 negative, so current stops in the right-hand anode and 37*R*. Tube 5 flashes the warning that a correction is given to speed the web.

23-7. Side-register Control (CR7505-S119).—While a web-register control "sees" printed marks pass lengthwise at high speed, a side-register control "looks" at the edge of such a web (of paper or metal) and "sees" only a small sidewise movement while the web is being wound onto a roll. When the web is lighter than the background, phototube 1 (Fig. 23*G*) receives more light if the web shifts toward one side, but it receives less light if the web shifts the other way. To keep the edge of the web from moving more than, say, $\frac{1}{64}$ inch sidewise, the circuit of Fig. 23*G* must respond to small and slow changes of light as the web shifts. No tubes in this circuit are capacitor coupled.[21-3] Many refinements are added to protect this circuit from outside voltage dips. The d-c supply from rectifier tube 9 and its filter (1*C*, *X*, 2*C*), is further smoothed by voltage-regulator tube[10-6] 7, so that the voltage 62-to-3 is held constant at 150 volts. Tube 2 is a pentode, whose filament current is held constant by ballast[28-15] tube 8. Large capacitor 5*C* braces the voltage at grid 68. These all are described in Chap. 10.

When phototube 1 "sees" the web shifting to one side, a d-c correction motor (upper right in Fig. 23*G*) moves the entire roll sidewise, to bring the web edge back to the right place; this makes a smooth-edged roll. This d-c motor has constant field current: the motor armature voltage comes from an amplidyne generator[28-2] (driven at constant speed by an a-c motor). Beam power[7-10] tubes 5 and 6 control the d-c fields of this generator so as to change the amount of voltage supplied to the correction-motor armature; in this way the d-c motor is turned in either direction or is stopped.

Some one position of the web is "just right"; at this position the d-c correction motor must not turn. At this best position, phototube 1 receives a certain amount of light and sets the control-grid 10 voltage of tube 2; however, the amount of tube-2 anode current can be increased by turning 3*R* clockwise

(lowering the cathode potential of tube 2). At the right setting of 3*R* we shall see that tube 5 passes the same amount of current* as tube 6 passes; the current in amplidyne field *F* is equal to the current in field *R*. These fields "buck," or oppose, so the generator sends no voltage to the d-c motor; the motor does not turn.

Let us see how phototube 1 controls tubes 5 and 6 and the d-c motor. When the web shifts and increases the light on tube 1, grid 10 rises and tube 2 passes more current; more electrons flow from 3 through 3*R*, 32*R*, tube 2 and 4*R* to the constant point 62.

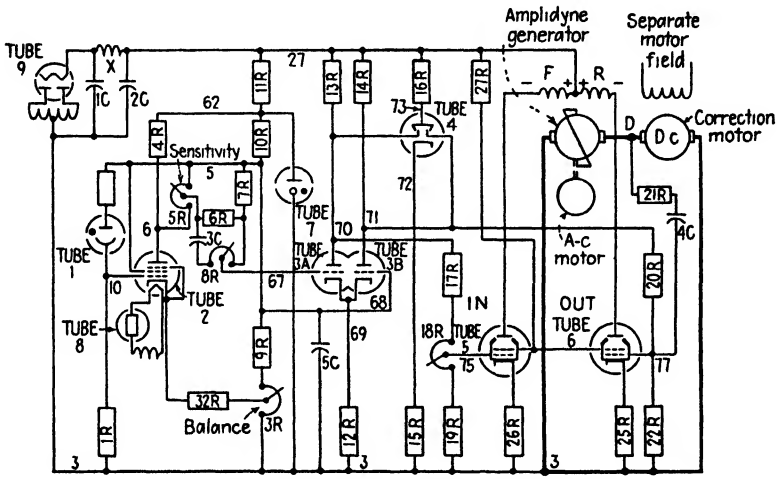


FIG. 23G.—Side-register control (CR7505-S119)

For awhile let us connect tube-2 anode 6 to the grid 67 of tube 3*A*. Greater tube-2 current lowers point 6 and grid 67, decreasing the current in tube 3*A*. Notice that tubes 3*A* and 3*B* are a "long-tailed pair"[16-5]; less current in 3*A* lowers cathode 69, increasing the current in tube 3*B*. In this way, the lowering of grid 67 raises the anode potential at 70, but lowers the point-71 potential. The grid-75 potential rises, turning on tube 5 and strengthening the *F* field; the grid-77 potential falls, turning off tube 6 and weakening the *R* field. Since field *F* is now so much stronger than the opposing field *R*, the generator sends armature voltage to turn the correction motor, which moves the roll so as to decrease the light reaching phototube 1.

* The anode current of tubes 5 and 6 may be balanced further by turning 18*R*.

Tube 4 is an indicator to show what correction is being made. Unlike tube *F* of Fig. 23*C* (see Sec. 23-3, footnote), this tube 4 has no triode amplifier. Instead, it has two deflecting wires, connected to points 70 and 71. Electrons flow through 15*R* and from cathode to circle anode of tube 4 and through 16*R*; the potential of the cathode 72 is not far from point 27. When tubes 3*A* and 3*B* pass equal currents, points 70 and 71 are slightly more negative than anode 73; each deflecting wire of tube 4 repels electrons away from a small part of the green circle anode, so this "eye" shows a small shadow wedge on each side of the circle. When point 70 rises and 71 falls, the shadow near wire 70 decreases, while the shadow near wire 71 becomes larger.

23-8. More Antihunt Circuits.—Now let us include (between tube-2 anode 6 and tube-3*A* grid 67) the resistors 6*R*, 7*R* and 8*R* and capacitor 3*C*. By turning 5*R* clockwise, the circuit is made less sensitive; the web shifts farther before the correction motor responds. Opposite turning of 5*R* may cause such quick action by the correction motor, that the equipment "hunts"—the motor moves the roll too far to one side and then too far in the other direction. To decrease such hunting, part of the voltage between anode 6 and point 5 (fixed by the voltage divider 11*R*, 10*R*, 9*R* and 3*R*) is applied across 3*C* and 8*R*. When light increases on tube 1 and point 6 drops to a lower potential, the voltage across capacitor 3*C* does not change at once; grid 67 is forced negative (as though connected directly to anode 6) but it then returns more positive as 3*C* discharges through 8*R*. In this way, the d-c motor is forced to turn quickly at first, then it slows down or stops until the effect of its correction can be seen at phototube 1.

Near the d-c motor in Fig. 23*G*, the circuit of 21*R* and 4*C* also decreases hunting. Notice that 21*R* is connected to one side of the d-c motor armature. This armature terminal *D* is made more negative (by the amplidyne generator) when field *R* carries greater current than field *F*. When the field-*R* current increases quickly, *D* becomes more negative so fast that capacitor 4*C* pushes grid 77 more negative, decreasing the current in tube 6 and field *R*. A second later, 4*C* has discharged through 21*R*, so that grid 77 returns to its earlier potential; the effect of 21*R* and 4*C* is to delay any sudden change of armature voltage, so that the whole circuit acts smoothly to give just the needed correction.

Questions

True or false? Explain why.

1. A diode acts like a contact that opens whenever the anode becomes more negative than the cathode.

2. In Fig. 23*C*, the signal at phototube 1 is amplified in five steps before it reaches the correction motor.

3. In Fig. 23*C*, the two halves of tube *E* act as a "long-tailed pair."

4. In Fig. 23*C*, pentode *G* acts like a contactor whose coil receives voltage through two control contacts in series.

5. When potential rises at the deflecting electrode of an electron-ray or indicator tube, the shadow increases.

6. In Fig. 23*C*, if 11*C* is not used, the wink of tube *F* may not be seen.

7. In Fig. 23*C*, if 28*R* burns open, tube 4 glows steadily.

8. In Fig. 23*C*, slider 3 on 13*R* sets the grid bias of tube *D*.

9. In Fig. 23*G*, if tube 3 is removed, the shadows on tube 4 increase.

CHAPTER 24

THY-MO-TROL—AUTOMATIC TUBE CONTROL OF D-C MOTORS

The speed of a d-c motor is easily changed or controlled by tubes, as described in Chap. 15. Rectifier tubes permit the d-c motor to operate from a-c supply lines. Of greater importance,

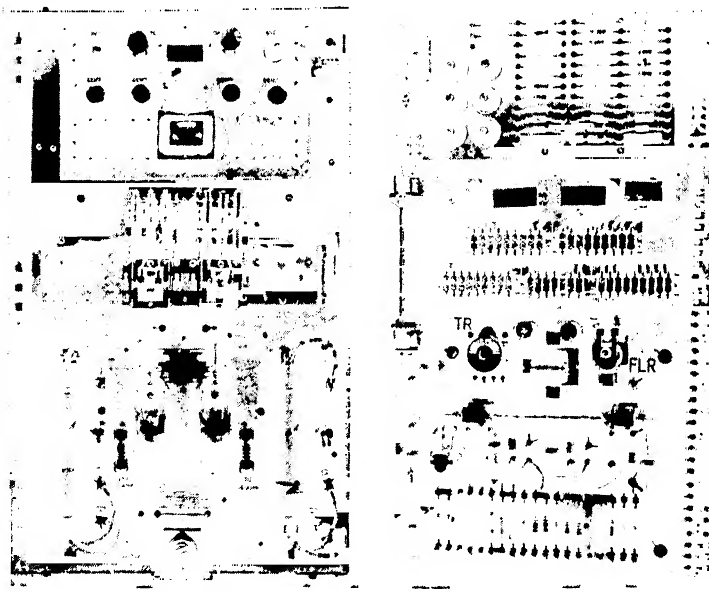


FIG 24A —Thy-mo-trol for a 2-hp d-c motor (CR7507-G)

such a tube-controlled motor can respond to sensitive high-vacuum tube circuits, as next described. Such a system provides the more accurate speed control and versatile motor operation that are needed by modern machine drives. Figure 24A shows a Thy-mo-trol used with a 2-hp d-c motor.*

* The Thy-mo-trol circuit used with motors of ½ hp or less is described in Chap. 25.

24-1. The Thy-mo-trol System.—A simple approach to this thyratron motor control is shown in Fig. 24*B*. The armature of the d-c motor receives its current through thyratron tubes 1 and 2, while the motor field is supplied by tubes 3 and 4. (A similar circuit appears in Fig. 15*D*, described in Sec. 15-3.) The man watching the meters in Fig. 24*B*, is like the "electronic control unit" or "brain" of the system, described later.

Thyratrons 1 and 2 are phase-shifted[13-1] by the a-c voltages of grid-transformer windings *S3T*, so as to change the average voltage across the motor armature. The primary *P3T* is in a phase-

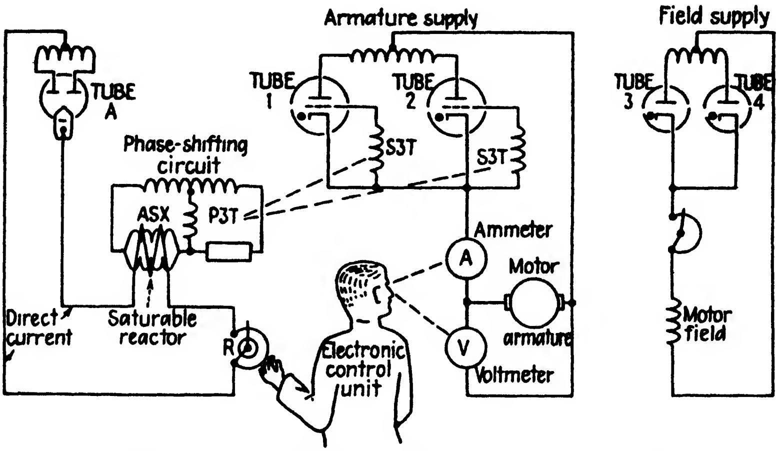


FIG. 24*B*. Basic arrangement of thyratron control of a motor

shifting bridge,[13-7] controlled by the saturable reactor *ASX*. Recall (from Secs. 14-1 and 16-4) that this reactor is controlled by the amount of direct current flowing in its d-c winding; this direct current depends on the setting of rheostat *R*.

In Fig. 24*B*, we see that tubes 1 and 2 control the voltage applied to the motor armature, in much the same way as a motor-generator set (with Ward Leonard field control) supplies variable voltage to a direct-current motor. That is, if rheostat *R* is shorted and permits maximum direct current to flow and saturate *ASX*, then tubes 1 and 2 supply maximum average voltage to the motor armature, and high speed results. However, when *R* is turned clockwise, decreasing the direct current in *ASX*, tubes 1 and 2 supply less average voltage to the motor armature, whose speed decreases.

The operator or man shown in Fig. 24*B*, who watches a voltmeter and ammeter in the motor-armature circuit, turns rheostat *R* so as to hold the desired motor voltage (and speed), and keep the motor current within safe limits. In the "brain" of the Thy-mo-trol several tube circuits are used in place of this operator, but the results are the same—(1) they "watch" the voltage across the motor armature; if the voltage drops even less than a volt, they cause an instant increase of direct current in *ASX*, causing tubes 1 and 2 to fire earlier in their half cycles, until the armature voltage returns to normal; (2) they "watch" the amount of motor-armature current; when that current reaches the preset limit (such as 150 per cent of rated full-load current) the direct current in *ASX* is decreased so that tubes 1 and 2 fire later, preventing any further increase in armature current.

Many thyratron control equipments provide a wider range of motor speed (as much as 100 to 1) than can be obtained from changing the armature voltage alone. Instead of holding constant field as shown in Fig. 24*B*, many control equipments include grid-controlled thyratrons for the field supply, as well as for the armature supply. Circuits are added in the "brain" to control these field-supply thyratrons; we shall see that these added field circuits are often duplicates of the armature-control circuits.

24-2. A "Streamlined" Thy-mo-trol.—A complete Thy-mo-trol circuit is shown in Fig. 24*C*. We say "complete," but we have omitted numerous protective resistors, grid-cathode capacitors, and even some of the complete circuits that ensure best performance. These will be added later.

At the top of Fig. 24*C* are thyratrons 1 and 2, which supply the motor armature; tubes 3 and 4 supply the motor field. The lower portion of Fig. 24*C* is the electronic control unit, or "brain," including all tubes marked by letter. All parts of this circuit operate on direct current, which is supplied by rectifier tube *A* (upper left). Let us first study this d-c supply of tube *A*, together with the left-hand portion of this "brain," to see how it regulates the motor-armature voltage. These circuits are shown alone in Fig. 24*D*.

Here we recognize tube *A* and the filter,[10-4] consisting of 10*C* and reactor *X*; together these provide a d-c supply between points 4 and 7. However, the amount of this d-c voltage can be affected by changes in a-c supply voltage. For the sensitive,

balanced circuits of the "brain," a closely regulated or constant supply of direct current is needed; it is obtained by the use of voltage-regulator tubes *B* and *G*. The voltage-regulator tube used here contains neon (shown by its orange glow). Its type designation, *GL*-75-30, shows that this tube maintains close to 75 volts across it when passing current of less than 30 milliamperes; this action is explained in Sec. 10-6.

Because of regulator tubes *B* and *G* we may think of point 6 as a d-c bus that is always 75 volts more positive than point 7; point 5 is always 150 volts above point 7, or 75 volts above point 6. Between 5 and 7 in Fig. 24*D* is a voltage divider[3-7] (2*R*, 3*R*, 4*R*). Notice that this divider is *not* connected to point 6.

24-3. Armature-voltage Control.—In Fig. 24*D*, *ASX* is the d-c winding of the saturable reactor that controls the phase shifting of armature tubes 1 and 2. This *ASX* d-c winding is in series with tube *D*, so tube *D* controls the amount of direct current flowing in *ASX* and, therefore, acts as does rheostat *R* shown in Fig. 24*B*. From now on, let us keep in mind that when *ASX* current decreases, the armature voltage likewise decreases. See now how tube *D* is controlled by tube *C*.

When tube *C* is passing no anode current, the voltage drop across resistor 2*R* is caused entirely by current flowing through 3*R* and 4*R*. Under this condition, the resistances of 2*R*, 3*R* and 4*R* have been selected so that point 9 (grid of tube *D*) is near the same potential as point 6 (cathode of tube *D*) so that tube *D* passes maximum current through *ASX* (which lets tubes 1 and 2 apply maximum voltage to the motor armature). If we now permit tube *C* to pass current (whose electrons flow from point 20 on potentiometer 7*VR*, through tube *C* to point 8, through 2*R* to point 5), this current increases the voltage drop across 2*R*. When this happens, there must be a corresponding decrease in drop across 4*R*; this causes the potential at point 9 (grid) to drop, so tube *D* decreases its current flow through *ASX*. Briefly, turning on tube *C* turns off tube *D* and thereby decreases the armature voltage.

Tube *C* is the comparison tube or "checker," which is told what armature voltage (speed) is desired; it then "watches" the armature voltage to see that it is correct. The cathode of tube *C* is connected to potentiometer 7*VR*, which is our means for setting the desired motor speed; the tube-*C* grid is connected to slider 22

on potentiometer $4VR$, which is not moved after it is once placed in service. Notice that this grid voltage, measured between points 22 and 7, is a fixed fraction of the voltage across the armature itself. Suppose that this fraction is $\frac{3}{10}$ so that, with 200 volts across the armature, the grid of tube C is 60 volts more

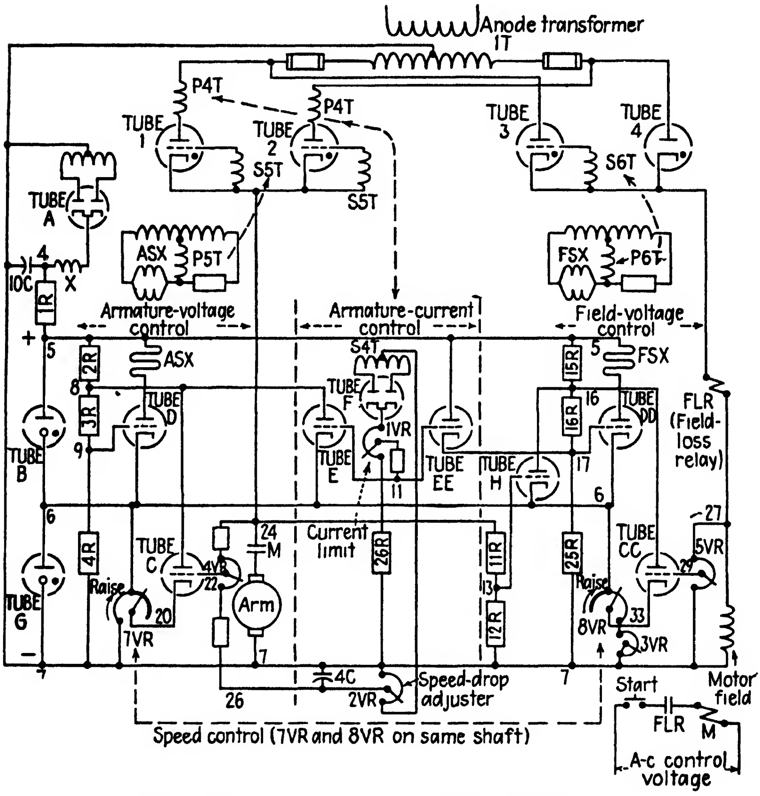


FIG. 24C.—Thy-mo-trol circuit, armature and field control.

positive than point 7. At the same time, assume that $7VR$, set for the corresponding speed, holds the cathode of tube C about 65 volts above point 7. Therefore, the grid is about 5 volts more negative than the cathode and tube C passes very little current. (Tube D therefore passes larger current, permitting tubes 1 and 2 to supply as much as 200 volts average to the motor armature. Conditions are balanced.)

To lower the motor speed slightly, you turn $7VR$ counter-

clockwise until the tube-*C* cathode is only 60 volts above point 7. This action lowers the cathode potential by 5 volts. (This has the same effect as raising the tube-*C* grid potential by 5 volts. Remember that a tube is controlled by only the *difference* in potential between grid and cathode.) Tube *C* passes full current, turning off tube *D*. Tubes 1 and 2 may "go out" entirely and pass no current for a moment while the motor slows down. When the armature voltage has decreased to say 185 volts, the tube-*C* grid potential has been lowered also; this partially turns

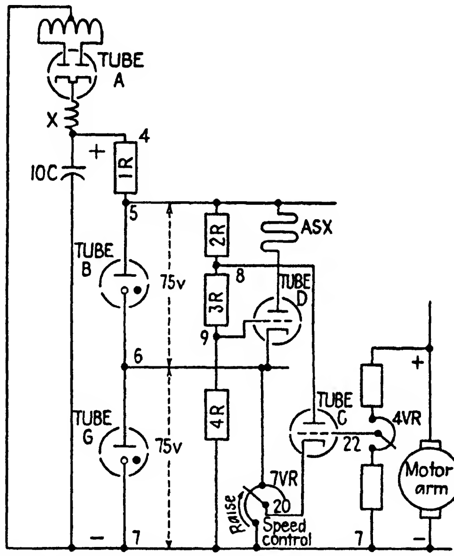


FIG. 24*D*.—Armature-voltage-control portion of Fig. 24*C*.

off tube *C*, turns on tube *D* and again applies just enough armature voltage to run the motor at the new desired speed.

Notice how tube *C* delicately balances or compares the motor-armature voltage against the desired standard (as set by 7*VR*). If a dip in a-c supply voltage causes $\frac{1}{10}$ volt drop in armature voltage, it also causes a tiny drop at tube-*C* grid; meanwhile tube-*C* cathode remains constant (thanks to the voltage-regulator tube *G*). This tiny voltage unbalance makes the tubes instantly swing into action and return the armature voltage to normal.

24-4. Field-voltage Control.—We have now studied the action of the armature-voltage-control circuit included at the left in

Fig. 24*C*. At the right is the field-voltage-control circuit; notice that it is a duplicate of the armature circuit just studied and operates from the same d-c supply (points 5, 6 and 7). It has the voltage divider 15*R*, 16*R*, 25*R*. Tube *CC* balances the fixed portion of the field voltage (at 5*VR*) against the desired field voltage as set by 8*VR*. An increase of tube-*CC* current causes larger voltage drop across 15*R*; the lowered potential at 17 decreases the current of tube *DD* through saturable reactor *FSX*, and thereby decreases the voltage that tubes 3 and 4 apply to the motor field.

While both tubes 3 and 4 may be thyratrons, each controlled by a *S6T* winding, Fig. 24*C* shows tube 4 as a phanotron, having no grid. To vary the voltage supplied to the inductive load of the motor field, only one tube needs to have a grid (as is explained in Sec. 15-12).

Notice that 7*VR* and 8*VR* are mounted on one shaft and are operated by a single dial. The right-hand half of 7*VR* is a dummy section of almost zero resistance; the same applies to the left half of 8*VR*. Turned to their extreme left, these potentiometers cause minimum motor speed, for the armature voltage is almost zero but the field current is large (tube *C* is full "on," tube *CC* is all "off"). Turning these potentiometers clockwise gradually increases the armature voltage but has no effect on the field voltage until the mid-point is reached. At the dial mid-point, the motor operates at base speed—full armature voltage and full field. Further turning clockwise has no effect on armature voltage but gradually decreases the field voltage and current, thereby causing further increase in motor speed. Notice that resistor 3*VR* adjusts and limits how far the cathode potential of tube *CC* can be lowered, and thereby limits the maximum motor speed.

After a 5-min period needed for warming the thyratrons, a time-delay relay (not shown) lets tubes 3 and 4 pass current. This field current picks up *FLR* (field-loss relay, at the far right in Fig. 24*C*), whose contact is in series with the start button; the line contactor *M* cannot close to start the motor unless field current is flowing. (*FLR* does not close, to permit starting the motor, unless both tubes 3 and 4 are passing current.)

24-5. Preventing Overvoltage.—There is one voltage control in Fig. 24*C* not yet mentioned. Suppose that the motor is

operating at high speed, obtained by turning the speed-control ($7VR$ and $8VR$) clockwise so that the field current is reduced. If the speed dial is now turned suddenly (counterclockwise) to a lower speed position, this change at $8VR$ increases the field current and the motor begins to slow down. The motor acts as a generator. With usual magnetic control the motor would "pump back" into the line; with tube control, the rectifier (one-way) action of the tubes prevents such pump-back, and therefore the voltage generated by the motor armature can become too high. To prevent this overvoltage, tube H is added in Fig. 24C (next to the field-voltage circuit).

Notice that the grid of tube H is connected to resistors $11R$ and $12R$, across which the voltage of the motor armature appears. As long as this armature voltage is less than 300 volts (for a 230-volt motor), the potential at point 13 (grid of H) is so far below point 6 (cathode of H) that tube H passes no current. However, when excess armature voltage occurs (as under conditions just mentioned), the increased voltage across $12R$ raises the grid potential (point 13) so that tube H passes current (electrons flow from point 6, through tube H and $15R$ to point 5). This current increases the voltage drop across $15R$, lowering the grid potential (17) so that tube DD decreases the current in FSX; this reduces the field current (although it opposes the action of $8VR$ and tube CC) so that the voltage generated by the motor is held within safe limits.

24-6. Current Control.—All the armature-control circuits this far have acted like the operator in Fig. 24B, while he looks only at the voltmeter. Since this "brain" must be able to control armature current, we must provide something to act like the ammeter in Fig. 24B, to indicate the amount of armature current. Therefore, in Fig. 24C we place a primary winding $P4T$ just above tube 1, and a duplicate $P4T$ above tube 2. These are windings of a current transformer, whose secondary $S4T$ is at the center of Fig. 24C. When current flows through tubes 1 and 2 (one half cycle through tube 1, the next half cycle through tube 2), a corresponding amount of alternating current flows in $S4T$; tube F rectifies this current into a pulsating direct current, so that electrons flow from the center tap of $S4T$, and up through $2VR$, $26R$, $1VR$ and tube F. When no current flows through tubes 1 and 2 or the motor armature, there is no current flowing

in *S4T*, tube *F*, *1VR* or *2VR*; all parts of that circuit are then at the potential of point 7.

24-7. Limiting the Motor Current.—When current flows through *S4T* and tube *F* (increasing as the armature current increases), this current produces a voltage drop across 26*R*; the potential rises at all parts of *1VR*, thereby raising point 11 (the grid of tube *E* and tube *EE*). This is the "current-limit" circuit and this is the way it works. For example, *1VR* is set at a point which may permit 150 per cent of rated armature current. As long as the armature current is less than this 150 per cent, there is not enough voltage drop across 26*R* to raise the potential at 11 high enough to cause tube *E* or *EE* to pass current.

However, with more than 150 per cent armature current, both *E* and *EE* come into action, to prevent any further increase in this current. Additional current passes through tube *E* and 2*R*; this lowers the potential at 9 (grid of tube *D*) and decreases the current through *ASX* (decreasing the armature voltage so that the armature current also decreases). But notice the opposite action of tube *EE*—we do not want it similarly to decrease the field voltage, for that would increase the motor speed and draw additional armature current. Instead, *EE* is connected so that its current passes through 25*R*; the increased voltage drop across 25*R* raises the grid potential 17 of tube *DD* and increases the amount of field voltage and current.

Both tube *E* and tube *EE* now act in the right direction; too much armature current causes tube *E* to turn off tube *D* (to decrease the armature voltage), but causes tube *EE* to turn on tube *DD* (to increase the field current). Note that point 17 (cathode of tube *EE* and grid of *DD*) is more negative than point 6 (cathode of tube *E*). Therefore, when increased armature current raises the potential of 11 (grids of *E* and *EE*), tube *EE* conducts first and applies full field before tube *E* reduces the armature voltage.

It appears as if a large number of vacuum tubes were used in the circuits of Fig. 24*C*. However, there are not so many separate tubes as the number of tube circles would indicate; tubes *C*, *D*, *E* and *F* are duplex tubes,[7-11] and each of these tubes includes the working parts often found in two separate tube enclosures. Tube *C* includes in its one enclosure all the parts marked *C* and

CC; it is a duplex triode, which includes two separate three-element structures. Tubes *D* and *DD* are contained in one tube enclosure. Similarly, tube *E* includes *EE* as well, while *F* and *H* are together. In addition to the armature and field thyratrons, a total of seven separate small tubes is required to perform all the operations of the control system of Fig. 24*C*; they work as if they were 11 small tubes.

24-8. Constant Speed with Changing Load.—Another important feature of the thyratron-control system remains to be described—its ability to keep the motor at constant speed, regardless of changes of motor load. This is more than we expect of a standard d-c motor operating from a constant-voltage supply. Even with constant armature voltage, we know that the motor speed usually changes when the motor load changes, because of the internal voltage drop (*IR* drop) of the motor. However, if we can increase the armature voltage a certain amount to match each increase in load, the motor speed can be held quite constant. The system includes a speed-drop adjuster (also called "*IR*-drop compensator"), which can automatically increase the armature voltage as the load increases. By proper adjustment of potentiometer 2*VR* (shown at lower center of Fig. 24*C*) the armature voltage is raised just enough to offset the motor's natural desire to slow down under the increased load, as explained next.

We have already seen that tube *C* calls for a correction of armature voltage if there is any change of potential at its grid (22). In Fig. 24*D* any slight decrease in armature voltage also decreases the grid potential of tube *C*; this makes tubes *D*, 1 and 2 act to increase the armature voltage. If we can cause this tube-*C* grid potential to drop also whenever the motor load increases, tube *C* will cause the armature voltage to increase and prevent speed drop.

Returning to Fig. 24*C*, notice that the tube-*C* grid is connected to potentiometer 4*VR*, which is part of a group of resistors connected between points 24 and 26. If we turn 2*VR* (the speed-drop adjuster dial) upward, so that its slider touches at point 7, then there is no voltage across 4*C*; point 26 is then at the same potential as 7, which is the lower terminal of the motor armature. With such a setting of 2*VR*, the grid of tube *C* "watches" only the motor-armature voltage, as we explained previously; it maintains constant armature voltage, regardless of motor load.

However, if $2VR$ is turned clockwise, so that a voltage appears across $4C$, this $4C$ voltage has an added effect on tube C.

The voltage across $2VR$ changes as motor load changes; it is caused by the current flowing in $S4T$ and tube F, as has been already mentioned.[24-6] Notice that this current through $2VR$ makes the slider of $2VR$ more negative than the top, point 7. This $2VR$ voltage contains ripples (for it is merely rectified a.c.), so the large capacitor $4C$ acts as a filter to remove the ripple from the voltage between points 26 and 7.

As the motor load increases and the voltage across $4C$ increases, the potential at point 26 is lowered; therefore, the potential at 22 (grid of tube C) is lowered also. Briefly, as armature current (motor load) rises, the potential at the slider of $2VR$ becomes more negative by a similar amount; this lowers the grid potential of tube C, which (through tubes D, 1 and 2) causes the armature voltage to increase. By proper adjustment of $2VR$ (speed-drop adjuster) this increased armature voltage will hold constant motor speed, despite changes in load.

To reverse a direct-current motor, the thyratron-control system uses "forward" and "reverse" contactors in the armature circuit, as shown in Fig. 24*E*.

When using ordinary d-c supply, we do not try to "plug" or stop a motor by reversing its armature leads, for we know that the inrush of armature current is too great. With the Thy-mo-trol system, such reversal is used, for the current-limit circuit is automatic; it reduces the armature voltage so that the inrush current remains within the desired limit.

24-9. A Complete 1-hp Thy-mo-trol (CR7507-G146).—The entire elementary diagram is shown in two parts. Figure 24*E* includes the motor with its armature- and field-supply tubes, phase-shifting bridge circuits and control station. The electronic-control unit, or "brain," appears in Fig. 24*F*. Notice five wires that bring armature and field voltages from the motor into the "brain"; transformer secondaries $S2T$ and $S4T$ appear in Fig. 24*F*, while their primaries are in Fig. 24*E*.

All the parts studied in Fig. 24*C* appear again in Figs. 24*E* and 24*F*. When the a-c supply circuit is closed, transformer $1T$ applies anode voltage to tubes 1, 2, 3 and 4; a winding $S1T$ furnishes 115 volts for the control station (right-hand side of Fig. 24*E*). Transformers $2T$ and $3T$ furnish filament voltages

to heat the tubes. The tap switch at one end of *P3T* must be set so that tubes 1 to 4 receive correct filament voltage, to give proper operation and long tube life.

Until *TR* finishes its 5-minute delay, notice that the *TR* contact disconnects one side of saturable reactor *FSX*; this prevents grid transformer 6*T* from firing tube 3, so there is little field current.* When *TR* contact closes, both tubes 3 and 4 fire, and the field current picks up field-loss relay *FLR*, whose contact closes in the push-button circuit. (Contact 1*CR* is already closed, since 1*CR* is picked up through the normally-closed contacts of motor contactors *F* and *R*, at the left in Fig. 24*F*.) If overload relay *OL* is closed, the motor may be started by either the "Forward" or the "Reverse" button. When the "Forward" button picks up *F* (whose *F* contact seals around 1*CR* and the button), two *F* contacts connect the motor armature to the positive (point 24) and negative (point 7) terminals of the rectifier (tubes 1 and 2). The motor speed rises to the amount set by the speed dials (7*VR* and 8*VR* in Fig. 24*F*); even if these dials are set at a high-speed position, the motor comes to this speed without drawing more current than is preset by the "current-limit" dial 1*VR* (at the right in Fig. 24*F*).

24-10. Starting the Motor.—To see how the motor-starting current is controlled, we must study several added circuits (not shown before in Fig. 24*C*). Near the center of Fig. 24*F*, notice tube *FF* and the contacts of *F* and *R* above it. Before either button is pushed, these *F* and *R* contacts are holding the tube-*E* grid at the potential of point 45 (midway between positive bus 5 and terminal 24 of the armature rectifier). Even if the armature-supply voltage (24 to 7) is very small, point 45 is more positive than cathode 6 of tube *E*. The circuit through these *F* and *R* contacts keeps tube *E* passing current so that tubes *D*, 1 and 2 are turned off; point-12 potential is also kept high so that tubes *EE* and *DD* cause full field current.

When starting the motor, contact *F* or *R* disconnects the tube-*E* grid 11 from point 45. The potential of point 11 now drops, for it is connected through 6*R* and 23*R* to slider 37 (far right in Fig. 24*F*). Until motor-armature current flows, *S4T*

* Although tube 4 passes anode current as soon as its cathode is hot, this current is very small compared with the current that may pass when tube 3 also fires (see Secs. 14-4 and 15-12).

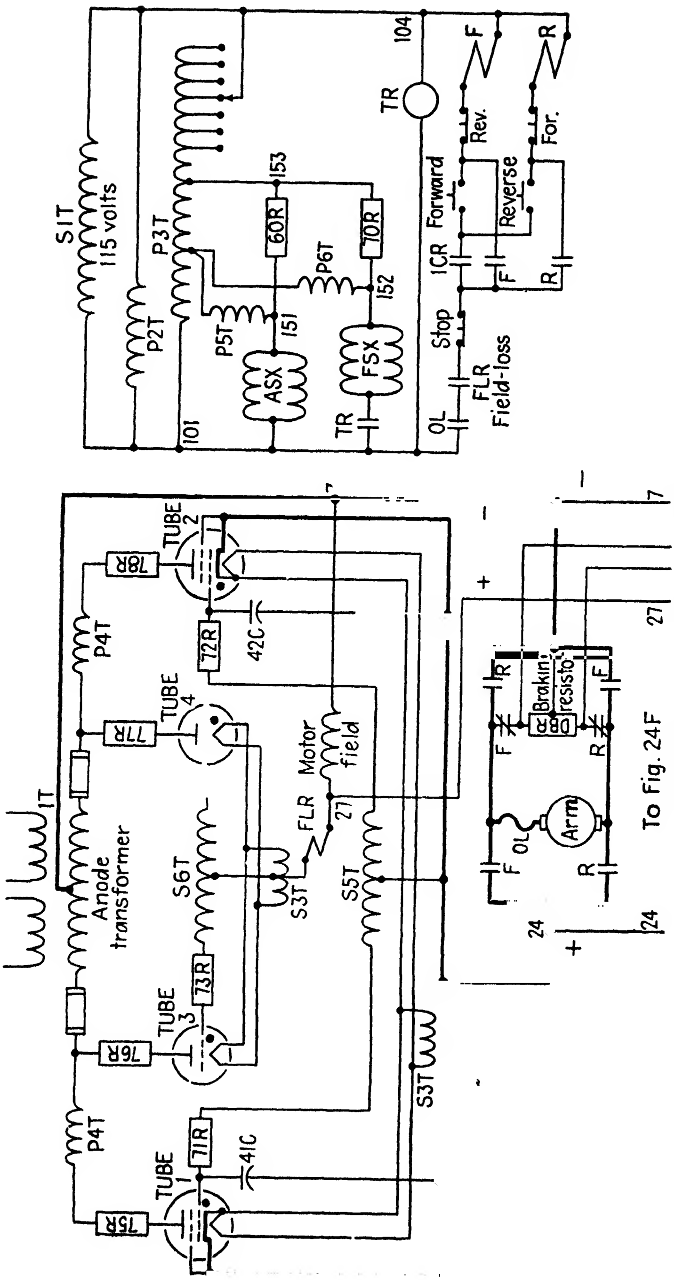


FIG. 24E.—Upper portion of 24F.

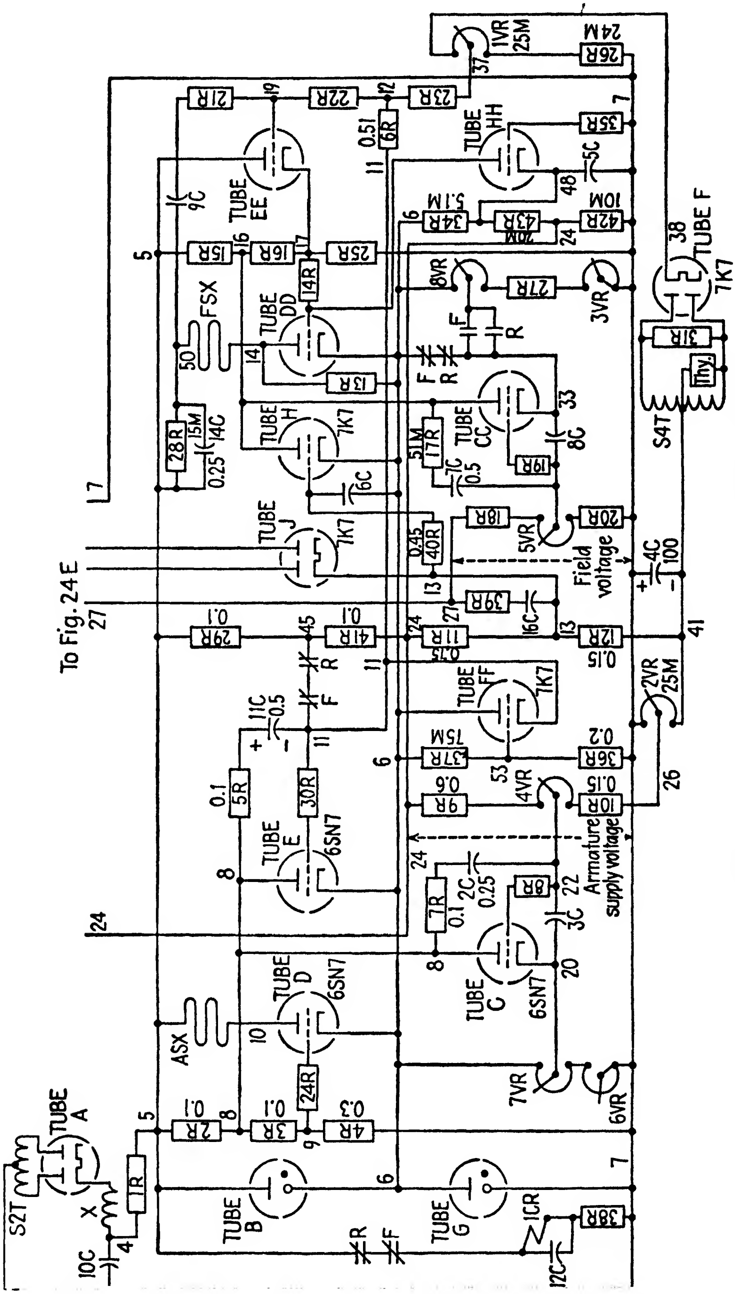


FIG. 24F.—Circuit of 1-hp Thy-mo-trol (CR7507-G146).

and tube F produce no voltage across $1VR$ and $26R$, so point 37 is near the potential of point 7 (which is 75 volts below cathode 6 of tube E). If grid 11 should approach this low potential, tube E would be turned off, tube D would be turned on,* and tubes 1 and 2 would permit a large inrush of current to the motor armature. To prevent grid-11 potential from dropping too fast, we add capacitor $11C$ and $5R$ between grid 11 and anode 8 of tube E. The voltage across $11C$ must change before grid 11 can change potential; $11C$ lets the grid-11 potential drop slowly, so that tube D turns on slowly and the armature current increases smoothly. Within $\frac{1}{10}$ sec this armature current (acting through transformer $4T$ and tube F) raises the potential at $1VR$ slider 37 high enough to prevent further drop of grid 11; after that, the "current-limit" control at $1VR$ has full effect.

Notice how $11C$ may cause an unwanted delay if the motor load suddenly increases; this delay is offset by adding tube FF. Without FF, suppose that there is very little load on the motor; with little armature current, there is little voltage across $1VR$ and $26R$. Grid 11 of tube E has reached a low potential at point 37, so $11C$ has charged to the large voltage between points 8 and 37. If the motor is suddenly loaded, the armature current can rise too high before tube E can be turned on to limit the armature current; this is because grid 11 has been at too-low potential and can rise to turn on tube E only after $11C$ has lost much of its charge. However, tube FF acts as a "snubber" (as is explained in Sec. 17-14) to prevent grid 11 from reaching such low potential. Since grid 53 of FF is held about 18 volts below point 6, FF has no effect as long as grid 11 remains near or above point 6. But when grid 11 drops to 12 or 15 volts below 6, the cathode of FF is now so near the potential of grid 53 that tube FF passes current; these electrons flow from point 7 through $26R$, $1VR$, $23R$ and $6R$ to point 11, through tube FF to point 6. Enough voltage drop appears across $23R$ and $6R$ so that grid 11 is held within 15 volts below cathode 6—just low enough to cut off the current flow† of tube E. When stopping or reversing the motor, contacts F and R again connect grid

* Here we assume that dial $7VR$ is in a high-speed position, so that tube C passes no current.

† Because of FF, tube E may *be prepared* at all times quickly to limit the armature current; for this reason, FF has been called the "Boy-Scout tube."

11 to point 45; tube *E* (helped by tube *FF*) turns on quickly, to prevent a large "plugging" or reversing current, as is described later.

Notice other contacts of *F* and *R* above tube *CC* (right center of Fig. 24*F*). Before the motor starts, these contacts connect cathode 33 to high potential 6, so that tube *CC* passes no current; tube *DD* passes full current to cause full field strength. When the motor starts, another *F* or *R* contact connects cathode 33 to the slider of 8*VR*; if 8*VR* is set (clockwise) at a high-speed position, cathode 33 is now at low potential and *CC* passes current through 15*R*, trying to weaken the field. However, *CC* has little effect as long as high armature current keeps tube *EE* turned on.

The tube-*C* circuit includes 2*C* and 7*R* to decrease hunting;[17-10] tube *CC* uses 7*C* and 17*R* while tube *EE* has 9*C* and 21*R*. For example, if the slider of 7*VR* is moved quickly to raise the motor speed, tubes *C* and *D* may respond so fast that the speed may not change smoothly. However, 2*C* is charged to the voltage between tube-*C* anode 8 and grid 22. When 7*VR* quickly raises cathode 20, anode-8 potential also rises; since the voltage across 2*C* cannot change instantly, the rise at 8 causes a rise at grid 22. For an instant, grid 22 keeps tube *C* passing current; as 2*C* charges, grid 22 slowly turns off tube *C*. In this way the unwanted swings of current are decreased.

Grid 22 of tube *C* receives voltage from 4*VR*, which (with 9*R* and 10*R*) is connected to the rectified output of tubes 1 and 2. Since this voltage contains sine-wave ripple, capacitor 3*C* is used to filter this voltage so that only d.c. appears between grid and cathode of tube *C*.

24-11. Slowdown by Dynamic Braking.—Pushing the stop button in Fig. 24*E* drops out both *F* and *R* contactors; this disconnects the motor armature from tubes 1 and 2, so the motor coasts to a stop. However, other *F* and *R* contacts now connect the armature across a braking resistor; the fast-turning motor acts as a d-c generator, forcing current through *DBR*. This quickly brings the motor to rest. The amount of this braking, or slowdown, depends on the amount of *DBR* resistance and the strength of the motor field; with no field current, the turning motor cannot generate—it merely coasts.

To prevent too-high armature voltage while the motor drops

to a lower speed, tube H responds to high armature voltage 24-to-7 (because of its grid connection through $40R$, $11R$ and $12R$), and then weakens the field.[24-5] However, when both contactors F and R are dropped out (as when the motor is stopping or reversing), the voltage generated by the motor armature does not reach point 24. The n-c F and R contacts connect 11 to 45, turning on tube E[24-14] so that tubes 1 and 2 supply little voltage 24-to-7. Other F and R contacts connect 33 to 6, turning off tube CC; this lets tube DD turn on tubes 3 and 4 and strengthen the motor field. To prevent too much field strength, (which might let the slowing armature generate high voltage across DBR), the ends of DBR are connected to anodes of tube J (center of Fig. 24F). The voltage between either end of DBR and its mid-point 7 now forces electrons to flow from 7 through $2VR$ and $12R$ to point 13, and then through tube J. If the motor produces high voltage across DBR, a large voltage appears across $12R$ and raises grid 13 of tube H so as to weaken the field, keeping lower armature-generated voltage.

24-12. Waveshapes of Armature Voltage.—Before watching the action of relay $1CR$ or tube HH, let us see what voltage is applied across the motor armature, at various speeds and motor loads. In (*a*) of Fig. 24G, the "Forward" contactor closes; at once tubes 1 and 2 fire, very late in the half cycles of anode voltage. The heavy jagged line in Fig. 24G shows the waveshape that might appear on an oscilloscope* connected between terminals 24 and 7 (of Fig. 24E)—the voltage applied to the motor armature.

As the armature turns, it generates a d-c voltage, which appears as a horizontal line (at L in Fig. 24G) during the time when tubes 1 and 2 are not passing current. This L voltage increases as the motor speed rises. Parts of the a-c voltage wave (from anode transformer $1T$) appear on the oscilloscope only during those parts of the cycle when tubes 1 and 2 are firing; at such times the tubes connect the transformer to the armature—at other times the oscilloscope shows only the d-c voltage generated by the motor itself. In (*b*) of Fig. 24G the motor is turning at medium speed, so its generated d-c voltage (called the *counter emf*) may be half the height of the available $1T$ a-c voltage wave.

* The oscilloscope must be arranged to indicate d-c voltage. See. footnote, p. 416.

At this speed, if the motor is loaded, tubes 1 and 2 must fire fairly early in each half cycle to let enough armature current flow to run the motor. At *B* the tube fires; however, only the voltage *M* can force current through the motor, for the rest of the a-c wave is opposed by the motor's generated voltage. Notice that armature current may flow, even after the a-c voltage has

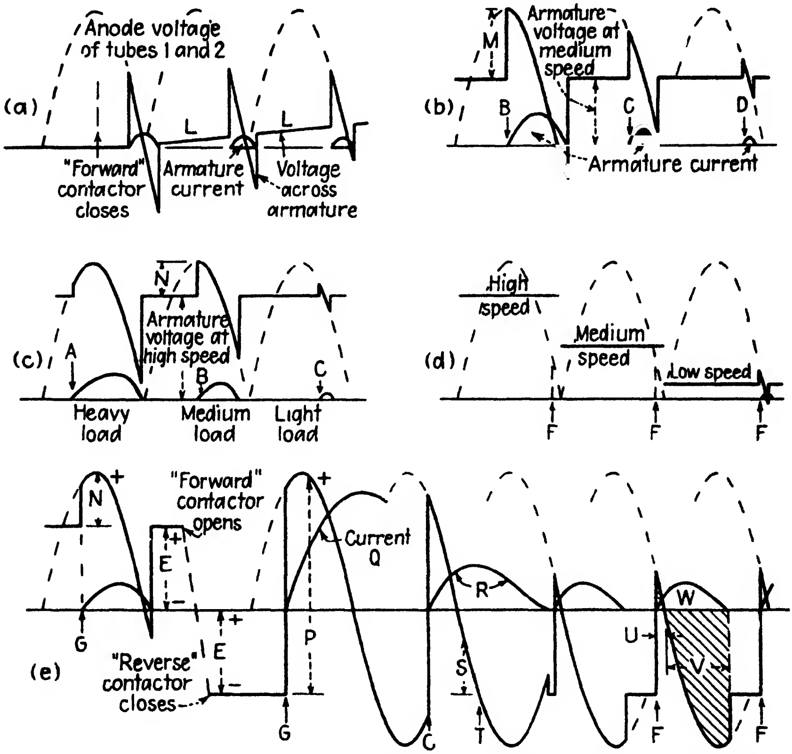


FIG. 24G. Waveshapes of armature voltage and current of d-c motor supplied through thyratrons.

reversed, for the energy (stored in the armature inductance by the flow of current) keeps the tube firing until the current has decreased to zero.[14-4] With less load, the tubes fire later (at *C*) and the armature current flows for a smaller part of each half cycle. Without load, the motor needs so little current that the tubes need not fire until *D*; here the oscilloscope picture is a straight line with a tiny jagged mark—a very small portion of the a-c voltage wave.

At high speed, (*c*) of Fig. 24*G* shows the high position of the straight line of d-c armature voltage. Only the voltage *N* (higher than the d-c generated voltage) can force armature current to flow. If the motor carries heavy load, the tubes must fire early (at *A*), so that armature current flows most of the time. At lighter loads, the tubes fire later (at *B* or *C*).

If we turn the speed dial (7*VR* in Fig. 24*F*) to a lower speed position, the firing of tubes 1 and 2 is delayed until late in the half cycle, shown at *F* in (*d*) of Fig. 24*G*. While the motor coasts* to a lower speed, the oscilloscope shows only the horizontal line of d-c voltage; this line gradually falls to a lower level as the speed decreases. When this d-c voltage reaches a low level, the tubes again fire, as shown at the far right in (*d*), to keep the motor turning at low speed.

24-13. Reversing the Motor; Inverter Action.—With the motor running in the forward direction, suppose that the "Reverse" button is pushed; this drops out *F* and picks up *R*, while the armature still is generating voltage. In (*e*) of Fig. 24*G*, the first half cycle shows the motor running forward at part speed, and *E* is the voltage generated by the motor. The voltage difference *N* is forcing armature current to flow, when tube 1 fires (shown at *G*).

When the "Reverse" button (in Fig. 24*E*) is pushed, the "Reverse" contactor connects the armature to the rectifier in the opposite direction; generated voltage *E* now adds to the a-c anode voltage, so that the total voltage *P* will force armature current to flow when tube 1 fires. If tube 1 now is permitted to fire at this same point *G*, notice the large current *Q*, which may damage the motor. By the delaying of the firing point of tube 1 until *C*, this current is decreased. Yet this current *R* is much greater than the current shown in (*b*), where tube 1 is fired also at this point *C*. With the motor reversed in (*e*), current flows through tube 1 and the armature in the same direction as before (for current *R* is above the zero line). However, even after the a-c voltage of anode transformer 1*T* has become negative, voltage *S* still can force armature current to flow.

* Faster slowdown is gained if another tube is added (in the "brain" of the Thy-mo-trol, but not shown), which lets contactors *F* and *R* drop out, connecting the armature across *DBR* until the motor reaches the desired speed. Then contactor *F* or *R* recloses.

Later than point *T*, armature current flows until the energy in the armature inductance is used.

Before the "Reverse" contactor picks up, suppose that we further delay the tube-1 firing point until *F*, near the end of the positive half cycle of anode voltage (lower right in Fig. 24*G*). During *V*, current flows through tube 1 and the armature in the same direction as during *U*. However, during *V*, this current is flowing during the negative half cycle of anode voltage—here energy is flowing from the motor armature, through tube 1 into anode transformer 1*T* and the a-c supply line. A half cycle later, tube 2 likewise fires late at *F* and lets the armature-generated voltage force energy into the a-c line. In this way, this rectifier circuit acts as an inverter, changing direct current (generated by the armature) into alternating current. This action loads the armature so that it quickly stops. At once it may turn in the reverse direction and reach the speed set by 7*VR*.

24-14. Time Delay before Inverter Operation.—Part (*e*) of Fig. 24*G* shows the need for delaying the firing point of tubes 1 and 2 during a reversing operation. This phase shift results when the *F* and *R* contacts (above tube *FF* in the center of Fig. 24*F*) connect grid 11 to point 45. However, these contacts must stay closed long enough to turn on tube *E*. Since motor contactors *F* and *R* may act so fast that this 11-to-45 circuit reopens too soon, relay 1*CR* is added (lower left in Fig. 24*F*). While motor contactor *F* or *R* is picked up, relay 1*CR* is not picked up, so the 1*CR* contact is open (near the push buttons in Fig. 24E). Now when the "Reverse" button is pushed and contactor *F* drops out, contactor *R* cannot pick up until the 1*CR* contacts close. As contactor *F* drops out, its normally-closed contact (near tube *G*) completes the circuit that connects the 1*CR* coil to the d-c voltage 5-to-7. However, 1*CR* does not pick up at once, for current first must flow through 38*R* to charge capacitor 12*C*, before enough voltage can appear across the 1*CR* coil. So, when the motor is being reversed, relay 1*CR* delays the pickup of the closing contactor, and makes sure that the 11-to-45 circuit has had time to phase back tubes 1 and 2 (to fire at point *F* in Fig. 24*H*).

24-15. Limiting Inverter Voltage.—In Sec. 24-5 we saw how tube *H* limits the armature voltage during slowdown; here let

us see how tube *HH* (far right in Fig. 24*F*) limits the voltage generated by the motor while reversing and inverting. The cathode of tube *HH* is connected to a voltage divider (34*R*, 43*R*, 42*R*) so that cathode 48 is far more positive than grid 7; tube *HH* passes no current. If the motor receives power through tubes 1 and 2, the armature voltage (applied across 42*R*) raises cathode 48 higher. However, when the motor is being reversed, the armature voltage drives point 24 more negative than point 7. If this voltage exceeds about 300 volts, cathode 48 is driven about 70 volts below point 6, or close to grid 7. Tube *HH* passes current; electrons flow from negative point 24, through 43*R*, tube *HH*, 14*R*, 16*R* and 15*R* to point 5. This *HH* current lowers the grid potential of tube *DD*, to decrease the field current and reduce the generated voltage.

24-16. A Thy-mo-trol Using Tachometer Speed Signals.—In the circuits above, the armature voltage of the motor is used as a signal to show the motor speed. To control motor speed more closely, a tachometer generator[28-1] is used, driven by the motor; the "brain" for use with this tachometer is shown in Fig. 24*H*. Often such a thyratron motor control changes only the armature voltage, leaving the field voltage constant; the portion of Fig. 24*H* to the left of the broken line provides such armature control. Additional field control is given by the right-hand portion of Fig. 24*H*.

For this more accurate speed control, notice the added voltage-regulator tube *K*; the voltage across 7*VR* is kept more constant than by using only tubes *B* and *G*. Tube *C* in Fig. 24*H* is controlled from 7*VR*; its grid-22 potential depends on the tachometer-generator voltage. Speed dial 7*VR* selects the desired speed, then tubes *C* and *D* control the armature thyratrons (not shown, but like those in Fig. 24*E*) to bring the d-c motor to that speed at which its tachometer generator produces enough voltage to turn on tube *C*. Since this circuit responds directly to speed, it needs no speed-drop adjuster (like 2*VR* at the bottom of Fig. 24*F*). Other parts of this armature-voltage-control circuit work like those in Fig. 24*F*. (This is not a motor-reversing control, so a single motor contactor *M* replaces contactors *F* and *R*.)

The field-control circuit (at the right in Fig. 24*H*) is controlled by the voltage across the motor armature. When the motor is running at low speed, the armature voltage 24-to-7 is small,

so point 17 (below *FSX*) is below the potential of point 6. Tube *EE* is turned on; electrons flow from point 7 through 14*AR*, 14*R*, 13*R*, *FSX* and tube *EE* to positive point 4. With large direct current flowing in *FSX*, thyratron tubes 3 and 4 (not shown) apply full voltage to the motor field.

This field voltage (applied across 11*R*, 5*VR* and 12*R*) controls the potential of grid 29 of tube *CC*. Slider 29 of 5*VR* adjusts the amount of full-field voltage; if 5*VR* is set for 230 volts, tube

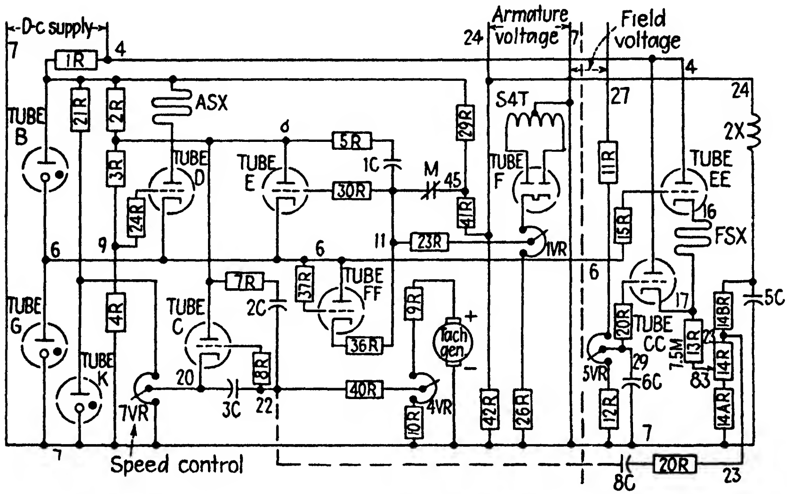


FIG. 24*H*.—Thy-mo-trol "brain" using tachometer speed signal.

CC passes no current while the field voltage 27-to-7 is below 230 volts. At 230 volts the grid-29 potential becomes high enough to let electrons flow from 83 through 13*R* and tube *CC* to 4. This increases the voltage drop across 13*R* so that points 17 and 16 rise, preventing further increase of current in tube *EE* and *FSX*; this action limits the maximum voltage that the thyratrons apply to the field.

As the motor speed increases, more armature voltage appears (24-to-7, at the right* in Fig. 24*H*); this voltage is filtered by 2*X* and 5*C*. The voltage between slider 83 and 7 increases so

* The broken-line circuit of 8*C* and 20*R* decreases hunting.[17-10] When greater armature voltage suddenly raises the potential at point 23, capacitor 8*C* carries this higher potential to grid 22; tube *C* passes more current to decrease the armature voltage. However, if the armature voltage increases slowly, 8*C* charges at this same rate and has no effect on tube *C*

that point 83 rises. Until the armature voltage rises to about $\frac{8}{10}$ of its full amount, the motor field has full strength (adjusted by $5VR$ and tube CC). However, as the armature voltage rises still higher (and the motor nears base speed),[15-2] the potential at cathode 16 rises enough to decrease slowly the tube-EE current and to weaken the motor field. Before the motor receives full armature voltage, its field voltage will be decreased. Notice that this circuit provides full-field strength until nearly full armature voltage is applied; then a further rise of armature voltage makes the field current decrease in order to raise the motor speed above base speed.

Questions

1. While the motor is running, in Fig. 24C, which tubes can fail or be removed without making the motor stop?

True or false? Explain why.

2. A thyratron can pass current for more than half of each cycle.

3. In Fig. 24C, if tube A is removed, tubes 1 and 2 fire and produce large armature voltage.

4. In Fig. 24C, if tube 3 fails, the motor may run too fast.

5. At low speed, the a-c voltage across the motor armature may be many times larger than the d-c voltage measured across it.

6. Until contact M (in Fig. 24C) connects the armature to point 24, $7VR$ cannot change the output voltage of tubes 1 and 2.

7. If $8VR$ is turned to the right (in Fig. 24C), the motor has less field voltage while starting.

8. With $1VR$ turned to the top (in Fig. 24C), the loaded motor stalls more easily.

9. If tube F is removed (in Fig. 24C), this has greater effect while the motor starts than when the motor runs, at normal load.

10. When a thyratron inverts, its current reverses.

11. In Figs. 24E and F, the motor and tube circuit will invert whenever the firing point of tubes 1 and 2 is delayed far enough.

CHAPTER 25

THY-MO-TROL FOR SMALL MOTORS

For variable-speed control of motors of ½ hp and less, a circuit is used that has most of the features of the large Thy-mo-trol of Chap. 24, but uses fewer tubes, as shown in Fig. 25*A*. This type of Thy-mo-trol has a different style of phase-shifting circuit,[13-1] described below; similar circuits appear in a tire-

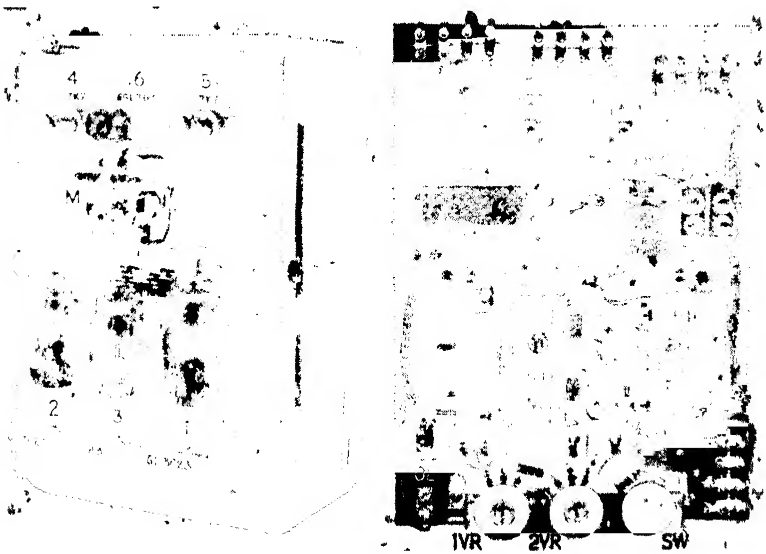


FIG. 25*A*. Thy-mo-trol for a ½-hp d-c motor (CR7507-F101).

building-machine drive and in an automatic battery charger, also described in this chapter.

25-1. The Small Thy-mo-trol (CR7507-F101).—The complete circuit, Fig. 25*B*, receives power through anode transformer 1*T*, from a single-phase a-c supply. Thyratron tubes 1 and 2 rectify[9-4] this a-c power, so that pulsating d-c voltage appears between points 24 and 7 and across the armature of the d-c motor. To vary the motor speed, the amount of this d-c volt-

age is changed by phase-shifting the tubes 1 and 2, as described below. To reverse this motor, reversing contactors must be added. The field of this motor receives d-c voltage from rectifier tube 3; this voltage remains unchanged (at about 230 volts), so the motor has constant field strength. This d-c voltage

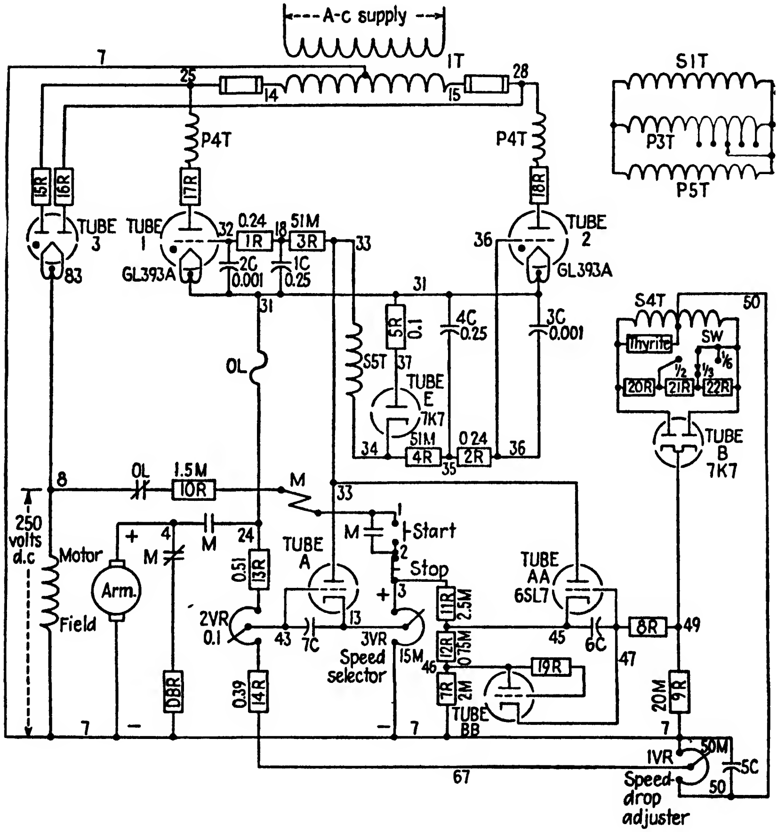


FIG. 25B.—Circuit of ½-hp Thy-mo-trol (CR7507-F101).

(between points 8 and 7) is also used to pick up contactor M, which connects the motor armature to the positive terminal 24. (Electrons flow from point 7 through $3VR$, the push buttons, coil M, $10R$ and the overload-relay contact OL, to point 8, through tube 3, alternately through $15R$ and $16R$ and fuses, to transformer $1T$ terminals 14 and 15.)

In Fig. 25B, all lettered tubes are in the "brain,"[24.1] which

controls tubes 1 and 2. Several of these high-vacuum tubes give results like those studied in Fig. 24*F*. Tubes *AA*, *B* and *BB* combine to limit the amount of motor-armature current. Tubes *A* and *E* control the phase-shifting of armature tubes 1 and 2; tube *A* is controlled by the speed dial 3*VR*. Let us see how an increase of tube-*A* current delays the firing of tubes 1 and 2, so that the motor speed decreases.

To explain the action of tubes *A* and *E*, Fig. 25*C* shows these tubes together with the phase-shifting circuit of thyratrons 1 and 2. (All parts are the same as those shown in Fig. 25*B*, but are arranged differently.) Transformer secondary *S5T* (in the

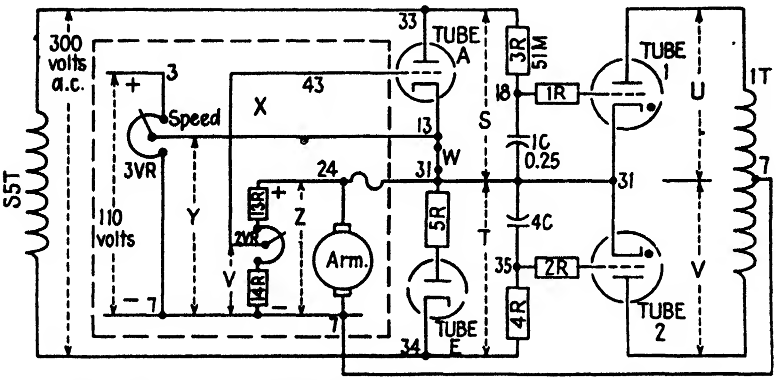


FIG. 25*C*.—Tube circuits for phase-shifting thyratrons of Fig. 25*B*.

center of Fig. 25*B*, but at the left of Fig. 25*C*) supplies about 300 volts a.c. between points 33 and 34. At first, do not use the circuits inside square *X*; place a wire at *W* to connect points 13 and 31.

Notice now that tubes *A* and *E* are in series; current may pass through these tubes and 5*R* only during the half cycle (shown at *P* in Fig. 25*D*) when terminal 33 is more positive than 34. During the other half cycle *N* (when tubes *A* and *E* pass no current and have no effect on the circuit) point 31 has a potential halfway between points 33 and 34, since 3*R* is equal to 4*R* and 1*C* is equal to 4*C*. During the positive half cycle *P* the potential at 31 depends on how much current passes through tube *A*. The high-vacuum triode *A* acts like a variable resistor—when its grid 43 is so negative that tube *A* passes little current, there is little voltage drop across 5*R* and tube *E*, so point 31 is more

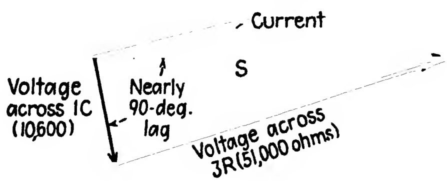
negative (than the mid-point between 33 and 34). When a more positive grid lets tube A pass more current, the greater voltage drop across $5R$ raises the potential of 31 until it may be much more positive than the mid-point.

25-2. Using Equal Half Cycles of Grid Voltage.—There is one value of grid potential that lets tube A pass just enough current so that point 31 is exactly halfway between 33 and 34; using this grid potential, the voltage S is equal to the voltage T during both half cycles of the a-c supply, just as if both tubes A and E were removed. More important, the size of voltage S stays the same during either half cycle P or half cycle N. Under this condition, let us see what grid voltage is applied to thyratrons 1 and 2.

The grid voltage of tube 1 is the same as the voltage across capacitor $1C$ (connected between grid 18 and cathode 31). Voltage S is applied across $1C$ and $3R$ in series; (similarly voltage T appears across $4C$ and $4R$ in series). This connection of $1C$ and $3R$ produces a wave of a-c voltage across $1C$ that lags* nearly 90 deg behind the voltage S, as shown in Fig. 25D. During half cycle P, voltage S is charging capacitor $1C$ so that its terminal 18 becomes more positive than 31, as shown at K. During half cycle N, the same voltage S discharges $1C$ and recharges it so that terminal 18 becomes more negative than 31, as shown at L. Since S is the same amount of voltage in either half cycle P or N, it raises the potential of point 18 as far above the 31 line (in half cycle P) at it lowers point 18 below the 31 line (in half cycle N).

The a-c anode voltage of thyratron tube 1 (marked U in Fig. 25C) is in phase with voltage S. As is shown in Fig. 25D, the

* Refer to Fig. 13E, where part (d) shows a similar circuit. As explained in Sec. 13-5, the 0.25 mu f capacitor $1C$ in Fig. 25C has 2660/0.25 or 10,600 capacitor ohms. The voltage across $1C$, and across the 51,000-ohm resistor



$3R$, is shown in this vector diagram. Notice that the a-c voltage across $1C$ is about one-fifth as large as the voltage S, or about 30 volts rms.

wave of grid voltage across $1C$ fires tube 1 at point K; a similar wave of grid voltage across $4C$ fires tube 2 at point L. So, as long as point 31 stays halfway between points 33 and 34 during both half cycles, P and N, the grid voltage of tubes 1 and 2 is an a-c wave (reaching equal distances above and below line 31), which delays the firing of tubes 1 and 2 until near the middle of the half cycles of anode voltage (U or V). Here the motor armature receives a medium amount of voltage (about half as large as can

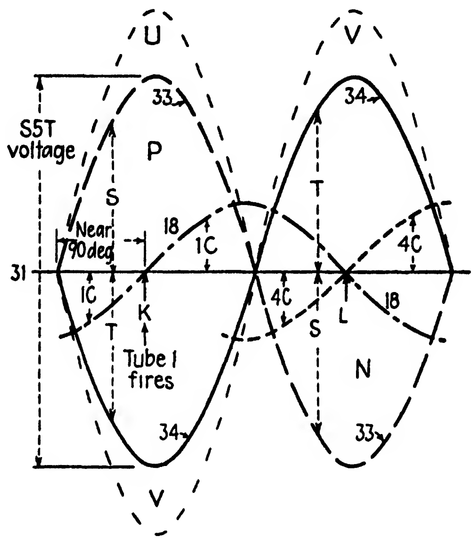


FIG. 25D. —Voltage waveshapes, firing thyratrons to cause medium motor speed.

be supplied when tubes 1 and 2 pass current during the entire half cycle).

25-3. Unequal Half Cycles for Phase Shifting.—If we now lower the grid potential of tube A in Fig. 25C so that less current flows through $5R$ and tubes A and E, the wave of grid voltage across $1C$ (or $4C$) does not change much in size or shape. As is explained below, the entire grid-voltage wave is raised higher above line 31, so that it fires tubes 1 and 2 earlier, increasing the voltage across the armature.

During half cycle N (while tubes A and E can pass no current), voltage S still is equal to voltage T, as shown in Fig. 25E. However, during half cycle P, the voltage drop across tube A is greater than the voltage drop across $5R$ and tube E, so the poten-

tial of point 34 becomes closer to point 31; point 33 rises higher above point 31. As a result, voltage S is larger during P than during N.

During P, this increased voltage S forces a larger current to charge capacitor $1C$, and terminal 18 rises higher above 31, reaching G. During N, voltage S is smaller and discharges $1C$ more slowly, so point 18 drops only to H. As a result of these unequal amounts of voltage S, we see that the point-18 potential follows a wave of the same shape as before, but the center line, or axis, of this wave is raised above 31 by the amount J. Notice that point 18 (grid of tube 1) becomes more positive than

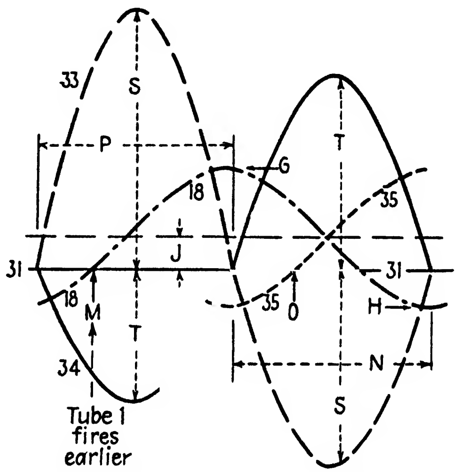


FIG. 25E.—Earlier firing of thyratrons—higher motor speed.

31 (cathode) at M, so tube 1 is fired earlier* in the half cycle of anode voltage.

As a result of lowering the grid potential of tube A, the a-c wave of grid voltage at 18 (or at 35) has been raised as if by a d-c voltage connected into the grid circuit of tube 1 (or tube 2). This is similar to the action described in Sec. 15-5 or in (b) of Sec. 13-15.

When the tube-A grid is made more positive, there is less voltage drop across tube A, so voltage S becomes less (during P) than its steady amount during N. As is shown in Fig. 25F, capacitor $1C$ receives less charge during P, so grid 18 rises less above the

* Likewise, voltage T (in Fig. 25E) is greater during N than during P, so the curve of point-35 potential is raised above 31 so that tube 2 fires earlier, at O.

31 line. The a-c curve of grid-18 potential now fires tube 1 at point R; this delayed firing of tubes 1 and 2 reduces the d-c armature voltage.

As the tube-A current changes, the resulting d-c voltage in the tube-1 grid circuit can be shown by a suitable d-c voltmeter connected across $1C$. Greater tube-A current drives the average potential of grid 18 more negative than cathode 31. We see that tube A produces d-c voltages across $1C$ and $4C$, which, by raising or lowering the a-c curve of grid potential, phase-shift the firing points of thyratron 1 and 2. Greater tube-A current causes less armature voltage. Now let us see what controls tube A.

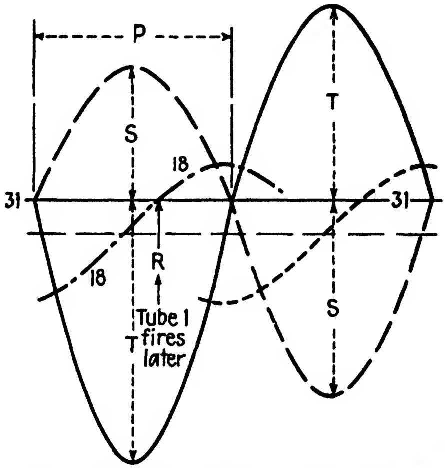


FIG. 25F.—Delayed firing and reduced motor speed.

25-4. Control of Motor Speed.—Remove wire W (center of Fig. 25C) so that cathode 13 and point 31 may be controlled from the circuits in square X. (Electrons flowing through tube E and $5R$ now must flow to point 24, to 7, to $3VR$ slider 13, then through tube A.) Between 13 and 31 we have inserted two voltages, Y and Z; when Y is equal to Z, points 13 and 31 are at the same potential. Suppose that the slider of $3VR$ is turned to touch at 3; this setting "asks for" the highest motor speed. Cathode 13 is now about 110 volts more positive than point 7, as shown by voltage Y. At high speed, the motor armature voltage Z may be 250 volts (or much larger than Y). However, the voltage divider ($13R$, $2VR$, $14R$) permits the voltage V to be less than

half as large as Z; at high speed, voltage V is also about 110 volts (or equal to Y), so that the tube-A grid 43 is near the potential of cathode 13. This grid voltage (nearly zero) lets tube A pass current so that tubes 1 and 2 supply about the right full-speed voltage to the motor armature. If this top speed is too high, the $2VR$ slider may be turned toward 24, to increase the tube-A current and decrease the armature voltage to produce the desired top speed. After this setting, $2VR$ is not changed.

To lower the speed, $3VR$ slider (in Fig. 25C) is turned away from point 3, to decrease voltage Y. This lowers cathode 13 so that tube A passes more current; this turns off thyratrons 1 and 2 until the motor coasts down to a lower speed. At this lower speed, voltages Z and V are smaller, lowering grid 43 to decrease the tube-A current and let tubes 1 and 2 supply a lower voltage to the armature. We see that Y is a d-c voltage standard whose size is selected (by turning $2VR$) to cause the desired motor speed. At this speed, voltage V becomes the right amount to control tube A so that tubes 1 and 2 supply the armature voltage needed at this speed.

25-5. Current Limit and Speed-drop Adjuster.—Returning to Fig. 25B, we see now that any increase of tube-A current makes tubes 1 and 2 decrease the armature voltage (and speed). Notice that tube-AA current will produce the same result; these electrons flow from $S5T$ terminal 34 through tube E and $5R$ to 31, through OL to 24, to 7, through $7R$, $12R$ and tube AA to $S5T$ terminal 33.

As is described in Sec. 24-6, motor current makes transformer winding $S4T$ (at the right in Fig. 25B) produce a voltage that is rectified by tube B (like tube F in Fig. 24C). As the motor current increases, a greater d-c voltage appears across $9R$ and $1VR$, so that the potential of point 49 rises. At large motor current, point 49 rises enough to turn on tube AA, to limit the armature voltage and prevent further rise of current.*

Tube BB prevents grid 47 of tube AA from dropping lower than point 46. (This is like the "snubber" action of tube FF described

* Above tube B, switch SW is set for the rating of motor used. For the smallest motor, resistors $20R$, $21R$ and $22R$ are all in circuit; they draw so little current that $S4T$ produces large voltage and turns on tube AA at a low amount of armature current. For a ½-hp motor, however, SW short-circuits $21R$ and $22R$, letting $20R$ draw larger current; this lowers the voltage that $S4T$ can produce, so that the armature current becomes larger before tube AA acts to limit this current.

in Sec. 24-10.) Therefore, if the motor load current increases suddenly, grid 47 can turn on tube *AA* quickly and limit the current. Capacitor 6*C* is needed to filter the ripples from the rectified voltage across 9*R*; 6*C* may delay the turning on of tube *AA* much unless tube *BB* is also used.

As greater load makes the motor draw more current, a larger d-c voltage appears also across 1*VR*. As is described in Sec. 24-8, the 1*VR* slider may be set so that this 67-to-7 voltage lowers the tube-*A* grid potential; this makes tubes 1 and 2 supply greater armature voltage, to prevent the natural slowdown of the loaded d-c motor.

Before the "Start" button picks up *M* (in Fig. 25*B*) to start the motor, there is no circuit between points 1 and 3 and no voltage across 3*VR*, 7*R*, 11*R* or 12*R*. Cathode 13 of tube *A* is at the low potential of point 7, so tube *A* is passing current and tubes 1 and 2 are turned off. In this way the circuit is "preconditioned," to prevent large starting current when *M* picks up.

25-6. The Tire-building Thy-mo-trol (CR7507-G219).—The motor-armature-control circuit described above is included in the control of a 2-hp motor driving a tire-building machine. Figure 25*G* shows the complete electronic circuit,* which varies both the armature voltage and the field voltage of the motor. Tubes 1 and 2 (controlled by tubes *A* and *E*) change the armature voltage; this voltage between points 24 and 7 is connected to the armature through reversing contactors *F* and *R* (similar to the armature-reversing circuit in Fig. 24*E*).

To stop the motor, contactors *F* and *R* are dropped out, so their n-c contacts connect the armature to *DBR*, to provide dynamic braking. While the motor slows down, its generated voltage (called its *counter emf*) keeps relay *CEMF* picked up; the *CEMF* contact (upper right in Fig. 25*G*) remains open until the motor speed drops the desired amount. After the "Stop" button is pushed, neither *F* nor *R* can pick up until *CEMF* drops out.

* Many extra dials are omitted, also the contactors that may select preset speeds for certain purposes. For example, the complete control adds dials (potentiometers), which may be used instead of 3*VR*, 4*VR* and 6*VR*; "Low-speed" or "High-speed" push buttons operate contactors that switch these dials into circuit. To permit hand-stitching the tire, the motor "creeps" at low speed; here the current limit is made so low that the motor and the tire are easily stalled if desired.

In the lower right-hand corner of Fig. 25*G*, transformer *S4T* and tube *B* supply a d-c voltage across 9*R* and 1*VR*; greater motor-armature current makes point 23 become more positive than 7. This voltage across 9*R* is connected across 16*R*, 15*R*

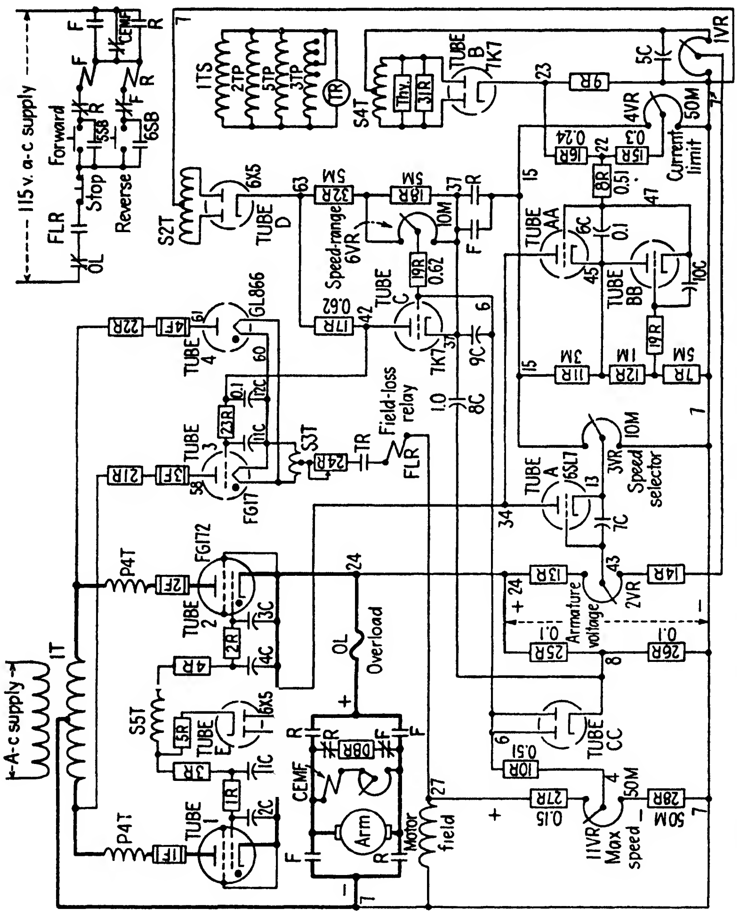


FIG. 25*G*.—Thy-mo-trol circuit for 2-hp motor on tire-building machine (CR7507-G219).

and part of 4*VR*, to provide a wide-range "current-limit" adjustment. If the 4*VR* slider is turned up to point 15 to prevent much armature current, point 22 (grid of tube *AA*) is about halfway between points 15 and 7 (when there is no armature current and no voltage across 9*R*). Since point 45 (cathode of tube *AA*) is at a fixed potential two-thirds of the range up from 7 to 15, point

45 is near the potential of grid 22; a very small armature current raises points 23 and 22 enough to turn on tube *AA* and limit the current. However, as 4*VR* slider is turned toward 7, the potential at 22 is lowered; now a much larger voltage must be produced across 9*R* before point 22 is raised high enough to limit the current.

Instead of having constant field voltage (as supplied through tube 3 in Fig. 25*B*), the motor of Fig. 25*G* receives its field current through tubes 3 and 4, which are phase-shifted to change the field voltage. (These electrons flow from point 7, through the field and *FLR* coil, *TR* contact and 24*R*, through filament transformer 3*T*, tube 3 or 4 to anode transformer 1*T*.) Only tube 3 needs to have a control grid,[15-12] to change the current in the inductive load of the field. Tube 3 is controlled by the d-c potential at point 42; we shall see that tubes 3 and 4 decrease the field current when tube *C* passes greater current. As is explained in Sec. 25-8, tube *C* is controlled by turning the same dial (3*VR*) that controls the armature voltage.

25-7. Phase Shifting the Field Tubes.—Through the middle of Fig. 25*G*, tube *D* supplies rectified d-c voltage between points 63 and 7, across a long voltage divider or "ladder."* From *S2T* mid-point 7 (above tube *D*), electrons flow through resistors 7*R*, 12*R*, 11*R* and contact *F* or *R* to point 37, and through 18*R*, 32*R* and tube *D* to *S2T*. Since this 63-to-7 voltage is not filtered, the potential at 63 rises twice each cycle (as shown in Fig. 25*H*). This voltage has size and waveshape equal to the 60-to-7 voltage supplied through tubes 3 and 4 to the motor field; therefore, point 63 may be at the same potential as point 60. Between 63 and 7, point 37 is the cathode of tube *C*; the 37 potential also rises above 7 but by a less amount. The changing voltage 63-to-37 is connected across tube *C* and 17*R* in series. The tube-*C* anode potential (point 42) is also the grid potential of thyratron tube 3.

When tube *C* passes no current,† there is no voltage drop across 17*R*, so that 42 has the same potential as 63. Since the 63 potential is now the same as the 60 potential (as mentioned above), grid 42 is also at cathode-60 potential; tube 3 fires at the start of

* In describing a voltage divider as a "ladder," we mean that you can "climb up" from one resistor to another to reach points of higher potential.

† This condition is not shown in Fig. 25*H*.

its half wave of anode voltage; therefore the motor field receives its greatest current.

When the potential of grid 6 rises (because of circuits described later), tube *C* passes current through 17*R*; therefore the potential of point 42 drops below that of 63. Let us see how this delays the firing point of thyratron 3 to decrease the field current.

Notice that 12*C* capacitor (in series with 17*R*) is connected between points 60 and 63 (in Fig. 25*G*). So long as there is no tube-*C* current and 42 is at 63 potential, no voltage will be applied to 12*C*; 12*C* has no charge and has no effect on the firing of tube 3.

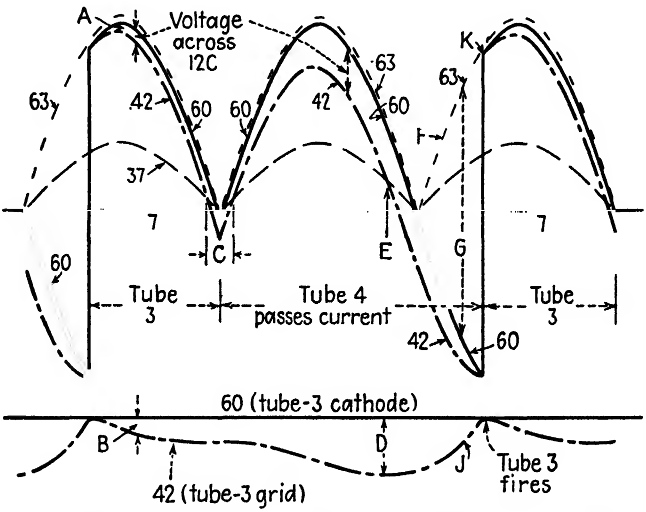


FIG. 25*H*.—Curves showing grid control of tube 3 in Fig. 25*G*.

However, when tube *C* passes current so that point 42 is at lower potential than 63 or 60, electrons flow from cathode 37 through tube *C* and into capacitor 12*C*, whose terminal 42 now becomes more negative than 60. As shown at *A* in Fig. 25*H*, the voltage across 12*C* increases slowly, because high-vacuum tube *C* acts as a large resistance through which the electrons must flow to charge 12*C*. This increasing voltage 60-to-42 is shown again at *B* in Fig. 25*H*. The charging stops during *C* but then resumes to produce a large 12*C* voltage at *D*. At *E* the decreasing point-60 potential and the charge on 12*C* make point 42 more negative than cathode 37, so that tube *C* (as a rectifier) stops passing current. However, the 12*C* voltage *D* still holds the tube-3 grid

more negative than cathode 60. Although the next half cycle of anode voltage (at *F*) tries to force current through tube 3, this action is prevented by the negative grid 42.

Since tube 3 cannot fire, the inductance of the motor field drives point 60 more negative than point 7 (as explained in Sec. 15-12 and Fig. 15*O*). The large voltage *G* now appears (in Fig. 25*H*) between points 63 and 60; this voltage is across 12*C* and 17*R* and makes 12*C* discharge through 17*R*. As the 12*C* voltage

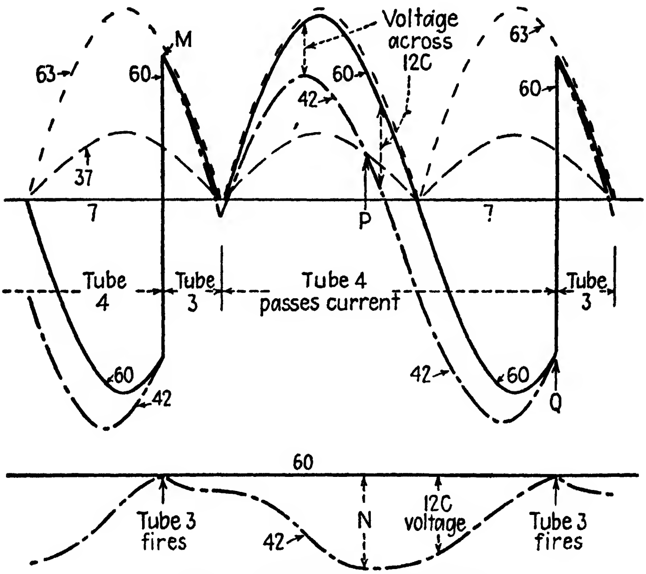


FIG. 25*I*.—Firing of tube 3, retarded.

decreases (as shown at *J*), grid 42 quickly rises toward cathode 60 and fires tube 3. At once points 60 and 42 rise far above 7 (at *K*) and the charging of 12*C* is repeated, as at *A*. Since the firing of tube 3 has been delayed, less d-c voltage is applied to the motor field.

Notice the difference when the tube-*C* current is increased, thus further lowering the potential at 42 (as shown in Fig. 25*I*). Although the charging of 12*C* begins later in the cycle (at *M*), tube *C* has less resistance to the electron flow, so that the voltage across 12*C* increases more quickly and reaches a large amount *N*. At *P* the tube-*C* current stops. The larger charge on 12*C* takes a longer time to discharge through 17*R*, so that grid 42 does not

approach cathode 60 until Q, late in the half cycle. Thyratron 3 fires so late that the motor-field current is greatly decreased. Here tube 3 is phase-shifted by the changing wave of voltage across $12C$ (as mentioned in (c) of Sec. 13-15). The field current decreases when greater tube-C current lowers the d-c signal potential at point 42.

25-8. The Field-control Circuit.—The grid-6 potential of tube C (center of Fig. 25G) is controlled through rectifier tube CC and is further adjusted by potentiometer dials $6VR$ and $11VR$. Through most of the motor-speed range, the potential at point 8 is so low that tube CC passes current; this connects the tube-C grid directly to point 8. Whenever the armature voltage is less than about nine-tenths of full value (as when the motor is starting, or $3VR$ is set so the motor runs below base speed), this grid-6 potential is so far below cathode 37 that tube C passes little current; therefore, tubes 3 and 4 apply full field current to the motor. As the motor nears base speed and the armature voltage rises, the rising potential at 8 lets grid 6 turn on tube C and weaken the motor field, running the motor above base speed (if $3VR$ is set in its high-speed range).

As increasing armature voltage raises point 8, notice that point 6 cannot rise higher than a potential nearly midway between $6VR$ slider and $11VR$ slider.* Point 8 may rise higher, but tube CC stops passing current, and disconnects 8 from 6. If the $11VR$ slider is turned clockwise, the tube-C grid potential is raised, turning off tube 3 further and raising the top motor speed to the desired amount. This top speed is raised further if the $6VR$ slider is turned (upward or counterclockwise, in Fig. 25G) to raise the grid-6 potential. Turning $6VR$ clockwise decreases the range through which the motor speed may be adjusted.

The motor-field current is also controlled indirectly from tube AA. Suppose that the motor is operating at high speed (weakened field) when a motor overload turns on tube AA, as described above.[25-5] This tube-AA current phases back tubes 1 and 2, so that the armature voltage decreases and the potential at point 8 drops. Tube CC passes current, lowering grid 6 to point 8; this turns off tube C, strengthening the motor field.

Notice how the circuits are "preconditioned"[25-5] when contacts F and R are open (right center of Fig. 25G) before the motor

* Here $19R$ and $10R$ act as a voltage divider between $6VR$ and $11VR$.

starts. These open contacts stop the flow of current through the voltage divider; point 15 drops to the low potential of point 7, lowering cathodes 13 and 45 so that tubes A and AA pass current, shutting off armature tubes 1 and 2. Also, point 37 rises to the high potential of point 63; the tube-C current stops, and point 42 rises, letting tubes 3 and 4 apply full field to the motor. Capacitor $8C$ charges to the high voltage between points 63 and 7; capacitor $6C$ has no charge. When contact F or R connects points 37 and 15, raising the cathode-45 potential, tube-AA current flows until $6C$ charges and lowers grid 47 below the potential of $4VR$ slider; this gradually turns on armature tubes 1 and 2. Also, when the closing contact (F or R) lowers cathode 37, the charge on $8C$ forces point 8 negative, so that grid 6 prevents tube-C current until $8C$ has discharged (through $26R$, to the steady voltage between 37 and 8).

25-9. The Phano-charger (CR7501-K115).—The automatic battery-charging circuit shown in Fig. $25J$ is like the simple charger described in Sec. 14-2; the a-c supply voltage is applied to a transformer $1T$ in series with a saturable reactor $1SX$. Two phanotrons 1 and 2 rectify this $1T$ voltage, and their output charges the battery. If no current flows through the d-c winding of $1SX$, most of the supply voltage appears across $1SX$ and little is across $1T$; the output voltage of tubes 1 and 2 is too small to charge the battery. An increase of direct current in $1SX$ raises the charging voltage.

This charging voltage (between 6 and 7) is also filtered[10-4] by $2X$ and $11C$, to produce steady d.c. across a divider ($4R$, $2VR$, $5R$); the potential at point 10 (control grid of pentode tube E) rises when the charging voltage rises. This voltage also supplies voltage-regulator tube D; although voltage 8-to-7 may change, tube D keeps tube-E cathode 9 at a potential 75 volts above point 7. This 75 volts is the standard, or reference, voltage[15-6] to which the battery voltage is compared; if that part of the battery voltage selected by $2VR$ is, say, 60 volts, grid 10 is 15 volts below cathode 9, so tube E passes little current. When higher battery voltage raises this 10-to-7 voltage (while cathode 9 remains 75 volts above 7), the tube-E current increases. We shall see that increased tube-E current delays the firing of thyratron tube B; this decreases the direct current in $1SX$, decreases the a-c voltage of $1T$, and lowers the battery-charging voltage.

Tubes A and B control the amount of d.c. in $1SX$, as described in Sec. 14-4, 14-5 and Fig. 14H. The a-c voltage supply to this circuit is taken from $1T$ at points 4 and 5; $1VR$ and $3VR$ act as a voltage divider, so that the a-c voltage M is selected for use. When thyratron B fires, electrons flow from point 4 through tube B and the d-c winding of $1SX$ to point 13; during the next half cycle (when 4 is more positive than 14, so tube B cannot pass cur-

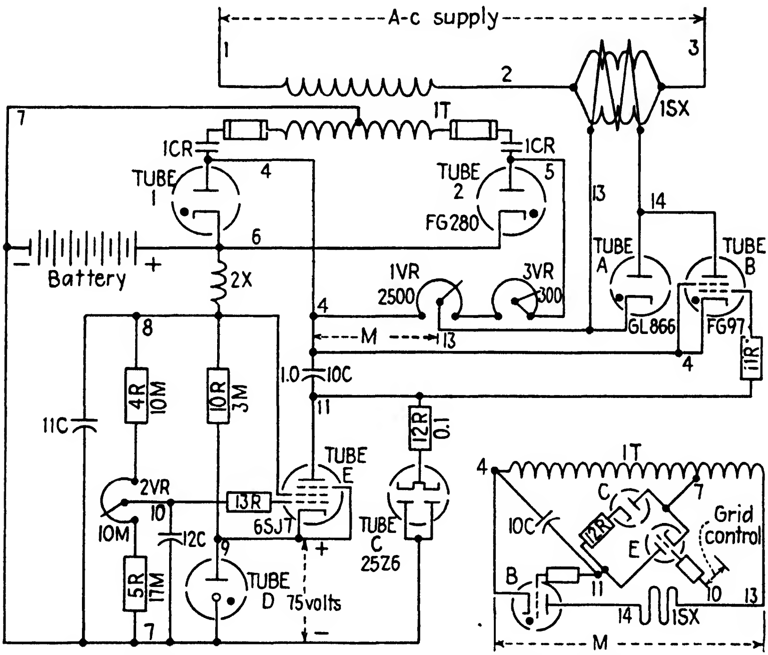


FIG. 25J.—Circuit of a Phano-charger (CR7501-K115).

rent) the energy stored in $1SX$ forces electrons to flow from 13 through tube A to 14. This steady flow of direct current in $1SX$ is decreased when tube B is fired later in its half cycle. Let us see how tube B is controlled by tube E.

25-10. The Capacitor-pliotron Bridge.—The voltage across capacitor $10C$ (middle of Fig. 25J) is also the grid voltage of tube B; $10C$ is charged by current flowing through tubes E and C. During the half cycle when the $1T$ voltage makes point 4 more positive than mid-point 7, electrons flow from 7 through tube D to point 9, through tube E into capacitor $10C$, to point 4; this

charging of $10C$ makes point 11 more negative than point 4. A half cycle later, electrons flow from 4 into $10C$, then through $12R$ and tube C to point 7; this flow makes point 11 more positive than point 4.

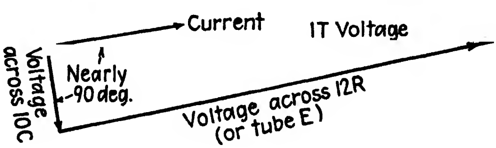
These circuit parts are shown again at the lower right in Fig. 25*J* (omitting tubes *A* and *D*). Suppose that tube *E* has the right grid-10 voltage so that the tube-*E* current (during one half cycle) is equal to the tube-*C* current (during the following half cycle). Notice that tube *E* now acts like a resistor of about the same ohms as $12R$;* this resistance (of $12R$ or of tube *E*) is in series with capacitor $10C$ to form a phase-shifting bridge, like that described in Sec. 13-5 or shown in (*d*) of Fig. 13*E*. The voltage across $10C$ is now a sine wave, which lags behind the $1T$ voltage by nearly 90 deg;† this $10C$ voltage fires tube *B* near the middle of its half cycle of anode voltage.

When greater battery voltage raises the grid-10 potential, the increased tube-*E* current now permits more electrons to charge $10C$; this electron flow is greater than can pass through tube *C* during the following half cycle, so the $10C$ terminal 11 remains more negative than before. This lowers the position of the wave of a-c voltage across $10C$, so that it fires tube *B* later in the half cycle. Similarly, if lowered battery voltage decreases the tube-*E* current, the electrons passing from 4 into $10C$ and through tube *C* remain unchanged, while fewer electrons flow through tube *E*. Terminal 11 of $10C$ becomes more positive, raising the position of the wave of a-c voltage across $10C$; tube *B* fires earlier, the d.c. increases in $1SX$, so greater $1T$ voltage increases the battery-charging rate.

In Fig. 25*J*, if the slider of $2VR$ is turned downward toward 7, the battery voltage must rise to a higher level before it will

* Here we assume little resistance in tube *C*, or no voltage drop across tube *C*.

† Since $12R$ is 100,000 ohms, and $10C$ is 1 mu f (or 2660 ohms[13-5]), the



vector triangle shows a small a-c voltage across $10C$, about 90 deg behind the $1T$ voltage.

turn on tube E; the battery becomes charged to a higher voltage. To reduce the charging current, the slider of $1VR$ is turned toward point 4; this decreases voltage M so that less direct current is forced through $1SX$, even if tube B is being fired at the start of its half cycle.

Questions

1. In Fig. 25B, if tube B is removed, which is correct?
   a. The motor runs at lower speed, or stops.
   b. No change in speed.
   c. The loaded motor runs at higher speed but may overload tubes 1 and 2.

True or false? Explain why.

2. There may be d-c and a-c voltage across a capacitor at the same time.

3. If tube (A and AA) is removed, in Fig. 25B, the motor-armature voltage is equal to the field voltage.

4. Current flows through tube BB of Fig. 25B at all times, since its grid and anode are connected together through $19R$.

5. With a-c anode voltage, a high-vacuum grid-controlled tube is like a variable resistance during both half cycles.

6. Since Fig. 25B includes no FLR relay (field-loss relay), this circuit has no protection against loss of field current.

7. In Fig. 25C, if tubes A and E are removed, the motor stops.

8. If tube (C and CC) is removed, in Fig. 25G, the motor has full field strength at all times.

9. In Fig. 25J, if $10C$ is shorted, the battery charging stops

10. In Fig. 25J, with a good battery, tube 1 or tube 2 may pass current during an entire half cycle.

11. In Fig. 25J, reactor $1SX$ is used for phase shifting.

CHAPTER 26

REGULATORS OF WELDING VOLTAGE AND CURRENT

Resistance-welding equipments (like those described in Sec. 12-2) may have to use power from a-c feeders whose voltage changes enough to prevent good results. The voltage-regulating compensator aims to remove this trouble. Also, when welding pieces of steel (or similar magnetic metals), the weld heat decreases as more of the metal enters the throat of the machine;* to hold constant welding current, the current-regulating compensator is used. Either of these electronic regulators may be added to a welding-control equipment that includes heat control by the phase-shift method, such as that described in Sec. 13-9.

26-1. The Voltage-regulating Compensator (CR7503-D157).—In Fig. 26*A*, the original or main welding-control equipment is shown at the right; this equipment must include a peaking transformer[28-5] in the grid circuits of the thyratrons that fire the welder ignitrons. This "peaker" is reconnected so that its primary winding is in the circuit of tubes 7 and 8 of the compensator; when tube 7 fires, ignitron *A* fires. Tube 8 makes another thyratron in the main panel fire ignitron *B*.

The a-c power supply to the welder also feeds transformer 1*T* whose secondary (lower left in Fig. 26*A*) applies voltage to the filament and control transformers, and to timing relay *TR*. After 5 min for warming the tubes, the *TR* contact closes to *P3T* and *P8T*, which furnish the anode power to thyratron tubes 7, 8, 10 and 11. As is explained later, if the *S3T* voltage decreases (showing that the welder voltage has decreased), the output of tubes 10 and 11 controls the amplifier tube ($2A + 2B$) so that thyratrons 7 and 8 fire earlier in their half cycles; this fires the ignitrons earlier and brings the weld heat back to normal, although the welder supply voltage is less.

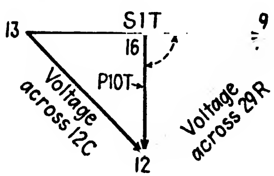
* The magnetic metal, passing between the welding electrodes and into the machine throat, increases the inductive effect of the high-current secondary winding; less current can flow through this greater inductance, so the heat at the weld becomes less.

The d-c voltage for this circuit is supplied through tube 1, and is filtered[10-4] by $1C$, $1X$ and $8C$. Voltage-regulator tubes[10-6] 4, 5 and 6 (with buffer resistor $1R$) keep voltages 2-to-10 and 10-to-7 at 75 volts each, and 7-to-6 at 105 volts. Between points 10 and 6 (180 volts), we find tube $2A$ and $6R$, also tube $2B$ and $10R$. These triodes act as a two-stage direct-coupled amplifier.[15-9] If the input grid potential rises at point 14, the increased tube-$2A$ current lowers point 11; this lowers grid 17 so that the tube-$2B$ current decreases, raising point 19. Any rise in point-14 potential moves the potential of point 19 upward also.

As the potential of point 19 rises, this d-c signal[15-5] fires tubes 7 and 8 earlier in their half cycles. Remove tube 9, so that the $S6T$ and $S8T$ voltages have no effect at points 45 and 44. The control-grid voltage of tube 7 is traced from point 45 through $19R$ and $S10T$ to point 19, through $10R$ to point 6, across tube 4 to point 7, cathode of tube 7; this grid voltage depends on the d-c signal voltage between points 7 and 19, and upon the a-c voltage of $S10T$. This $S10T$ voltage lags behind the tube-7 anode voltage* by about 90 deg; when point 19 is at the same potential as cathode 7, tube 7 fires near the middle of its half cycle.

When tube 7 fires, the voltage of $S8T$ forces electrons to flow from midtap 52 through $21R$ and $P4T$ or through $23R$† and P, and from cathode 7 through tube 7 to terminal 41. Both $P4T$ and P are the primary windings of peaking transformers; each

* At the lower left in Fig. 26A, $P10T$ receives its voltage from a fixed bridge made of $S1T$, $29R$ (5000 ohms) and $12C$ (0.5 mu f or 2660/0.5 = 5320



ohms). The vector diagram shows that the voltage from $S1T$ center tap 16 to junction 12 is nearly 90 deg out of phase with $S1T$ (or $S8T$).

† Resistors $23R$ and $24R$ act merely as a voltage divider, so that the desired portion of the $S8T$ voltage is applied to P, the primary of the peaking transformer mounted in the main welding-control equipment. Similarly, $21R$ and $22R$ let only half of the $S8T$ voltage be applied to $P4T$.

of their secondaries produces voltage peaks only at the instant when tube 7 (or tube 8) fires.*

When point 19 becomes more positive than 7, the a-c wave of $S10T$ voltage is raised so that it crosses the fixed cathode-7 line earlier in the half cycle, firing tube 7 (and tube 8) earlier. Lowering the point-19 potential delays the firing of tubes 7 and 8 and delays the firing of ignitrons A and B.

26-2. The Welding-voltage Signal.—Suppose that tubes 10 and 11 (center of Fig. 26A) have no grids and act like phanotron rectifiers.[9-1] Now the entire voltage wave of $S3T$ is rectified and is used to charge capacitor $9C$. (Electrons flow from $S3T$ midtap 20 through $13R$ to cathode 8, through tube 10 or 11 to $S3T$.) This rectified voltage has ripples, so $9C$ and $12R$ act as a filter;[10-4] steady d-c voltage appears across $9C$. Part of this $9C$ voltage is used (between 8 and $2P$ slider 14) to control amplifier tube $2A$.

If the heat-control dial (slider of $1P$) is turned to 7 for "full heat," point 8 is 75 volts more positive than cathode 10 of tube $2A$. If the 8-to-14 voltage is 77 volts, grid 14 is 2 volts more negative than cathode 10; tube $2A$ passes enough current to let point 19 rise high and fire tubes 7 and 8 early. Perhaps this fires ignitrons A and B so early that the welding transformer receives the entire wave of a-c supply voltage. If the supply voltage now decreases, the regulator circuit cannot increase the welder voltage to return the welder heat to normal. Therefore, slider 14 of $2P$ is turned clockwise to lower the potential of points 14 and 19 and delay the firing of tubes 7 and 8, so that (at normal amounts of supply voltage, and with $1P$ set for "full heat") perhaps only nine-tenths of the voltage wave is used by the welder. With this correct setting of $2P$, a small gap remains in the welder-voltage wave, which can be closed by earlier tube firing, to offset a drop in supply voltage.

To decrease the welder heat, turn the $1P$ slider toward point 10; this lowers the potentials of points 8, 14 and 19, so tubes 7 and 8 are fired later.

After setting the $1P$ and $2P$ sliders, watch the circuit regulate the welder voltage. If the supply voltage decreases (which lowers the weld heat of the usual welder), the $S3T$ voltage is less,

* A transformer is said to be *shock-excited*, when it is suddenly connected (like $P4T$ or P) to a voltage at a point later than the start of the voltage half cycle.

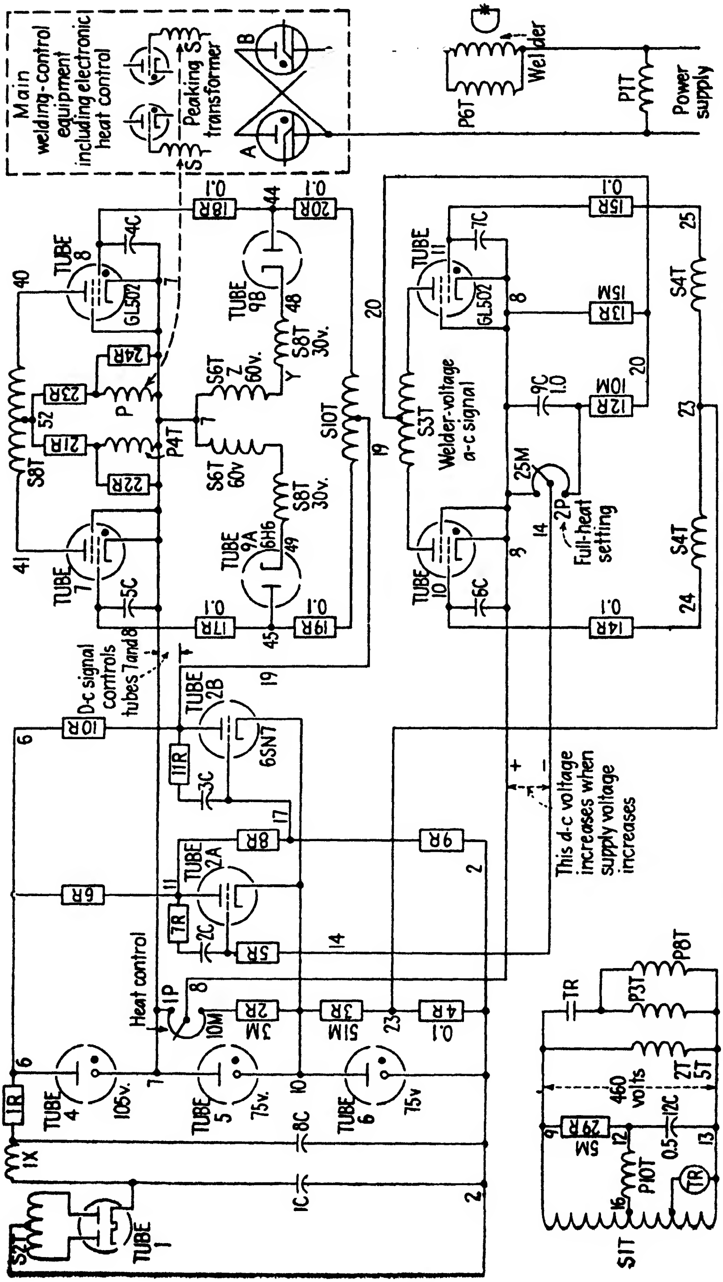


FIG. 26A.—Voltage-regulating compensator for resistance welding (CR7503-D157).

so there is less voltage 8-to-14. This lets the potential of grid 14 rise, so point 19 rises also and advances the firing point of tubes 7 and 8; the ignitrons fire earlier, so that a larger part of the a-c supply-voltage wave is applied to the welding transformer, to offset the reduced height of the supply-voltage wave.

To hold constant welding voltage, this circuit should not "watch" the amount of voltage during each entire half cycle, but only that part of the voltage wave when welding current is flowing. To do this, tubes 10 and 11 are grid-controlled. During the early part of each half cycle, tubes 10 and 11 do not fire, for their grids (at point 23, about 25 volts below point 10) are far below their cathodes (at point 8, at least 15 volts above point 10). However, when tube 7 fires, transformer $4T$ produces a voltage peak that raises point 24 above cathode 8, firing tube 10. A half cycle later, the firing of tube 8 makes $S4T$ raise point 25 to fire tube 11. In this way, there is voltage across $13R$ only during a time when there is voltage across the welding transformer. The filtered voltage across $9C$ is a signal from the during-weld voltage, and includes no signal from the earlier parts of the half cycles or from those cycles when the ignitrons do not fire.

26-3. Preventing Firing Only One Ignitron.—So far, tube 9 in Fig. 26*A* has not been included. The circuit of tube 9 (and the $S6T$ and $S8T$ windings near it) has an effect only when tube 7 or tube 8 fires too early in the a-c half cycle. Without tube 9, this early firing of tube 7 may let ignitron *A* pass current, but ignitron *B* does not fire. This prevents a normal weld; it may saturate the welding transformer and blow a main fuse. Part (*a*) of Fig. 26*B* shows why only one ignitron fires. Suppose that tube 7 is made to fire at point *D*, which is earlier than the normal power-factor angle[12-11] of the welder. Ignitron *A* passes current* for more than a half cycle, as shown by the shaded area. Without tube 9, tube 8 fires at *E*, causing the peaking transformer *P* to produce its voltage peak also at *E*, attempting to fire ignitron tube *B* at this point. However, ignitron *B* cannot start to pass current earlier than point *F* (or until ignitron-*A* current stops), for only about 15 volts appear across both ignitrons until point *F* is reached. At *F*, the peaker voltage *E* has already passed by, and ignitron *B* cannot be fired; only ignitron *A* passes current.

* This is a transient current, described in Sec. 12-11.

The circuit near tube 9 is added to delay the firing of tube 8 so that the resulting voltage peak does not occur until point F, just at the instant when current stops flowing in ignitron A.

This condition is shown again in part (b), and tube 7 starts the weld at D, ahead of the power-factor angle. Notice that the curve of grid voltage of tube 8, instead of following $S10T$, which crosses the cathode line at E, is now made to follow a different path between points G and H; this delays the firing of tube 8 until point J is reached. This change in the curve of grid voltage is caused by the tube-9 circuit.

Near tube $9B$ in Fig. $26A$, the $S8T$ winding Y always supplies 30 volts a.c., in phase with the anode voltage of tube 8; the $S6T$ winding Z supplies 60 volts a.c., 180 deg out of phase with the Y voltage. However, this $S6T$ voltage appears only while either ignitron tube is passing current, thereby connecting voltage to the welding transformer. Just to the left of point K, in Fig. $26B$, the voltage of $Y + Z$ keeps cathode 48 of tube $9B$ more positive than the tube-$9B$ anode (point 44). Since this permits no tube-$9B$ current, there is no connection through tube $9B$ between points 48 and 44, so the Y and Z voltages of $S8T$ and $S6T$ are not connected into the grid circuit of tube 8. However, after the tube-8 anode has become positive, to the right of point K in Fig. $26B$, notice that the added Y and Z voltages soon force cathode 48 to become more negative than point 44; tube $9B$ instantly connects points 48 and 44, and the tube-8 grid voltage now switches (at G in Fig. $26B$) to the $Y + Z$ curve of $S6T$ and $S8T$ voltages combined. In this way, the grid potential of tube 8 becomes more negative until point H is reached. At H, current stops flowing through ignitron A, and the Z voltage of $S6T$ instantly becomes zero. With no $S6T$ voltage, cathode 48 becomes more positive than anode 44, and the tube-$9B$ current stops; this disconnects windings Y and Z from the grid circuit of tube 8, and the grid voltage of tube 8 returns to the voltage wave of $S10T$. At J, tube 8 finally fires instead of earlier at point E. Point J is the proper place to excite the peaker transformer so as to fire ignitron tube B (after ignitron A has fired early, at D).

Part (c) of Fig. $26B$ shows a more normal condition; the point-19 potential is lower, so that the welder is operating at less than full heat, and each ignitron tube is being fired much

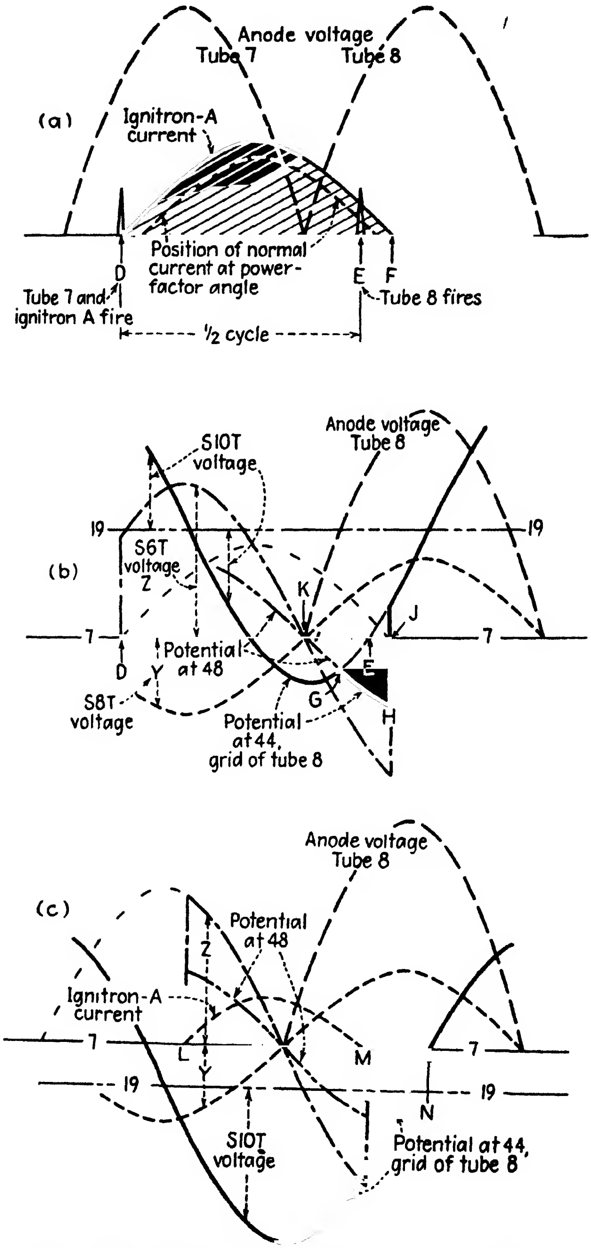


FIG. 26B.—Action of tube 9B to prevent firing only one ignitron.

later than the power-factor angle of the welding transformer. Current starts to flow in ignitron A at point L, and stops at point M. No attempt is made to fire tube 8 until point N. Point 48 (cathode) never becomes more negative than anode 44, so tube $9B$ passes no current; the Y and Z voltages have no effect on the firing of tube 8.

Even when the welder is being operated normally at a heat-dial setting as low as 50 per cent, there is need for the tube-9 circuit. For example, if some power disturbance should cause a large dip in supply voltage for a few cycles, the potential at points 14 and 19 rises rapidly, thereby causing tubes 7 and 8 to attempt to fire much earlier, perhaps far ahead of the normal power-factor angle.

26-4. The Current-regulating Compensator (CR7503-D160).—Some welding machines lose heat gradually when the work metal enters the welder throat. Even though the supply voltage may stay constant,* a current-regulating compensator is needed to advance the firing point of the ignitrons to keep constant current at the weld.

The complete circuit of this compensator appears in Fig. 26C; much of its upper portion is the same as Fig. 26A. The power supply at the right-hand side, with the welder, transformer $1T$ and $6T$ and the main welding-control equipment, is the same. A current transformer $C.T.$ is added, which "watches" the current flowing through ignitrons A and B and in the welding-transformer primary winding; if this current decreases (giving less heat at the weld), $C.\ T.$ sends less current to $P5T$, so the $S5T$ windings produce less voltage (above tubes 12 and 13).

Notice that the circuits of tubes $2A$, $2B$, 7, 8 and 9 are the same as in Fig. 26A and are explained above. If the potential rises at point 14 (tube-$2A$ grid, at the left in Fig. 26C), this raises point 19 (tube-$2B$ anode), and fires tubes 7 and 8 earlier; the peaking transformer P (mounted on the main welding-control equipment) makes ignitrons A and B fire earlier, increasing the welding current and heat.

Instead of voltage-regulator tubes, this circuit uses a voltage-regulating transformer[28-9] or stabilizer ($S2T$, upper left in Fig. 26C). The rectified output of tube 1 is filtered by $1X$ and $1C$, so

* If the supply voltage decreases, the compensator corrects for this change also.

that a steady and constant d-c voltage appears between points 6 and 2. A voltage divider (1*R*, 2*R*, 2*P* and 3*R*) sets the potentials at points 7, 8 and 10.

Between points 8 and 2, notice tube 3 in series with 4*R*. This tube is merely a high-vacuum rectifier tube, but it has "emission-limited" operation; the amount of current passing through this tube depends on the heat of this tube's filament. All the electrons emitted by its special cathode* pass to anode 14 and through 4*R*. We shall see that the tube-3 filament heat is raised by increasing the voltage produced by *S7T*. If the welding current increases, the *S7T* voltage also rises, increasing the emission of electrons and the current flow through tube 3 and 4*R*; the increased voltage drop across 4*R* lowers the point-14 potential, so that tubes 7 and 8 fire later and the welding current decreases, as is explained above.[26-1]

26-5. Electronic Switching to Heat Tube 3.—If welding current flowed at all times, the tube-3 filament could be heated directly from *C.T.* in Fig. 26*C*. However, most spot or seam welding requires the flow of welding current for short times, separated by "cool" times when no current flows. During these cool times (or before the weld begins), the tube-3 filament must not cool; it must be kept near the during-weld temperature, to be ready to give correct control as soon as welding current starts to flow. Therefore, whenever no welding current flows, the tube-3 filament is heated from a stand-by supply, provided by transformer 9*T*; during the weld, the filament is switched† or connected to transformer 5*T*, so it is then heated by current that changes as the welding current changes.

This switching of the tube-3 filament is done by thyratron tubes 10, 11, 12, and 13, grouped in one corner of Fig. 26*C*. In the center of this group is *P7T*, whose secondary heats the tube-3 filament. Notice how these tubes act as a double-throw contactor.

When no welding current flows, tubes 10 and 11 are passing current. During one half cycle, a *S9T* winding forces electrons

* Many kinds of tube cathode are damaged if the filament is cooled until all its electrons flow to the anode.

† Some types of current-regulating compensator include a magnetic contactor to switch the tube-3 filament from 5*T* to the stand-by supply. However, since this contactor may have to operate many times each second, it is replaced here by all-tube switching.

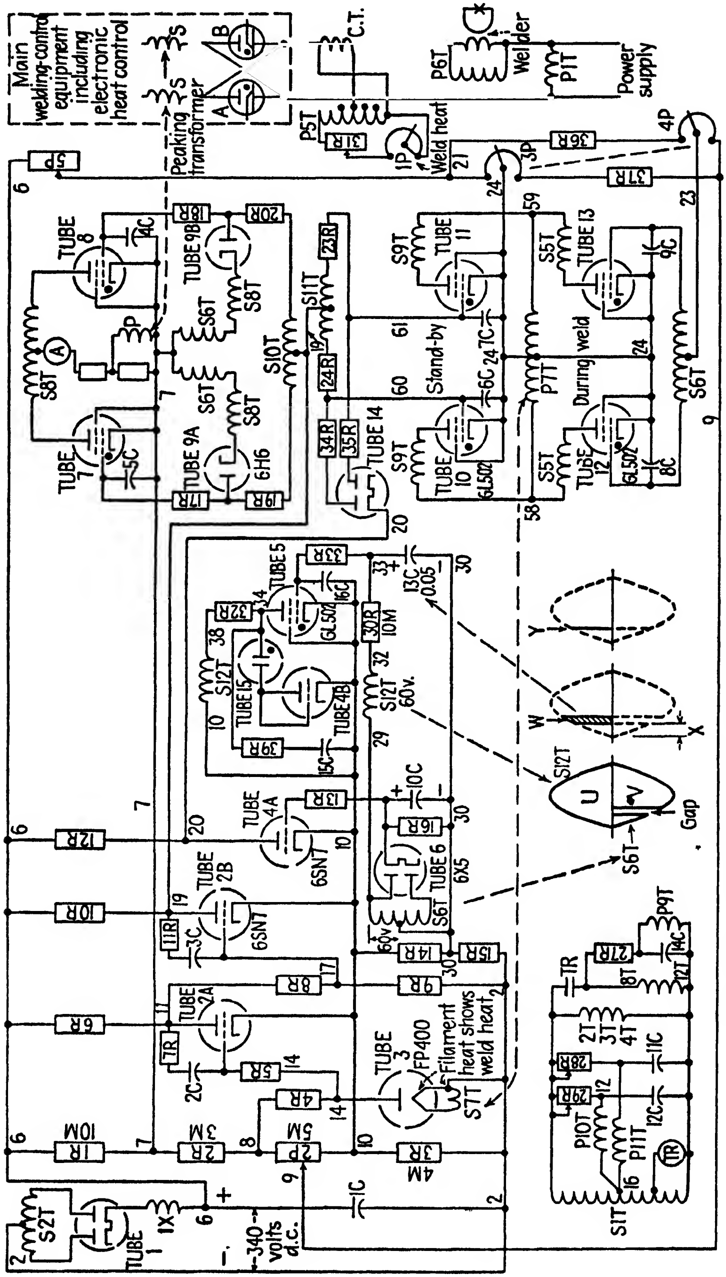


FIG. 26C.—Current-regulating compensator for resistance welding (CR7503-D160).

to flow from terminal 58 through $P7T$ to midtap 24, cathode to anode of tube 10, to $S9T$; a half cycle later, the other $S9T$ winding forces electrons to flow from 59, through $P7T$ to 24, through tube 11 to $S9T$. When welding current flows, tubes 10 and 11 are "turned off," as is explained later; at the same time, tubes 12 and 13 are "turned on." The voltage produced by one $S5T$ winding now forces electrons to flow from terminal 58 through $P7T$ to midtap 24, cathode to anode of tube 12, to $S5T$; a half cycle later, the other $S5T$ winding forces electrons through $P7T$ and tube 13. In this way, tubes 12 and 13 connect the tube-3 filament (through $P7T$) to $S5T$ during a weld; between welds, tubes 10 and 11 connect $P7T$ to the stand-by voltage of $S9T$.*

When no welding current is flowing, the tube-3 filament heat is adjusted† by turning $3P$; the $3P$ slider sets the cathode-24 potential of tubes 10 and 11 (for $3P$ is part of a voltage divider $5P$,‡ $3P$, $37R$). Meanwhile, the control grids of tubes 10 and 11 receive an a-c voltage from $S11T$, through $24R$ and $23R$. ($P11T$, in the lower left-hand corner of Fig. 26C, receives a voltage that is phase-shifted by $28R$ and $11C$, so that it lags about 90 deg behind the $S1T$ voltage.) The potential of point 19 (mid-point of $S11T$ and also of $S10T$) is raised or lowered by the action of tube $2B$. When greater tube-3 current lowers point 14 and the lowered point 19 delays the firing of tubes 7 and 8, the lowered point 19 also delays the firing of tubes 10 and 11; this decreases the $P7T$ voltage so that the tube-3 filament heat decreases, lowering the tube-3 current.

Meanwhile, tubes 12 and 13 pass no current, since $S5T$ furnishes no anode voltage for these tubes (while no welding current flows). Also, the tube grids are held at the potential of slider

* After TR contact closes (lower left in Fig. 26C), $P9T$ receives voltage from $S1T$. However, $27R$ and $14C$ combine to make the $P9T$ voltage lag about 30 deg behind the $S1T$ voltage. Therefore, although tubes 10 and 11 are fired late by the $S11T$ voltage wave, a large portion of the $S9T$ voltage wave is still applied to $P7T$ for heating the tube-3 filament.

† To help in this adjustment, a milliammeter A shows the current passing through tubes 7 and 8; this current increases if these tubes are fired earlier in their half cycles. While welding, this current depends on the weld heat desired; suppose that A indicates a current of 12 ma. Then, when welding current has stopped, $3P$ is turned until A again indicates 12 ma. With this setting, the tube-3 filament has about the same heat, whether the machine is welding or not welding.

‡ Sliders on $5P$ and $2P$ are factory adjustments, not to be changed.

23 of 4*P*, which is about 30 volts more negative than the 3*P* slider 24, cathode of tubes 12 and 13. (A shaft connects 3*P* and 4*P*, so that their sliders turn together; therefore, the voltage between these sliders is always the same at any setting.)

26-6. Action While Welding Current Flows.—When the flow of welding current starts (controlled by other circuits, not shown, in the main welding-control equipment), voltage appears across the welding transformer and across *P*6*T*. Secondary windings *S*6*T* now produce voltage for four purposes. (1) The action of the *S*6*T* windings near tube 9 has been explained.[26-3] (2) Another *S*6*T* winding turns on tubes 12 and 13, by producing an a-c voltage (between 4*P* slider 23 and the control grids), which is in phase with the *S*5*T* anode voltage.* The tube-3 filament is now heated (through *P*7*T*) from *S*5*T*. (3) The last *S*6*T* winding (near tube 6) has two actions; one is to control the signal tube 15, as is explained later. (4) This last *S*6*T* voltage is also rectified by tube 6, to turn off tubes 10 and 11 (as next explained) and disconnect the tube-3 filament from the stand-by supply of *S*9*T*.

Until this *S*6*T* voltage appears, no electrons pass through 16*R* or tube 6, so 10*C* has no charge. The grid of tube 4*A* is at the potential of point 30, which is so far below cathode 10 that tube 4*A* passes no current; with no voltage drop across 12*R*, point 20 is at the high potential of point 6, so cathode 20 of tube 14 is so positive that tube 14 has no effect. However, when the *S*6*T* voltage appears, it is rectified by tube 6 and produces a voltage drop across 16*R*. Capacitor 10*C* is charged to this voltage, raising the grid potential of tube 4*A*. Electrons now flow from 10 through tube 4*A* and 12*R* to 6. As the potential at point 20 is lowered, the cathode of tube 14 becomes so low that current flows through tube 14, 23*R* and 24*R*, and lowers the control grids 60 and 61, so that tubes 10 and 11 cannot fire, no matter what potential exists at point 19.

While welding current flows, the amount of this current may be adjusted by turning 1*P* (at the right in Fig. 26*C*); this is now the heat-control dial, in place of the similar dial on the main welding-control equipment. When 1*P* is turned clockwise, so that all the 1*P* resistance is in circuit, little current flows through 1*P* and 31*R*, so a large voltage is produced across *P*5*T* by the *C.T.*

* The *S*5*T* windings now furnish voltage, since welding current flows through *C.T.*

current; the $S5T$ and $S7T$ voltages are also large, raising the tube-3 filament heat. Of course, tube 3 at once passes more current, lowering points 14 and 19, delaying the firing of tubes 7, 8, A and B, so that lowest heat is supplied to the weld. When $1P$ is turned up, shorting its resistance, more current flows through $31R$ and $P5T$, lowering the voltage across $P5T$. The tube-3 filament receives less voltage; points 14 and 19 rise, firing tubes 7, 8, A and B earlier and increasing the heat at the weld. At the "full-heat" setting of $1P$, enough of $31R$ should be in circuit, so that tubes A and B pass current during only about nine-tenths of each cycle, as the weld begins; then, as more metal enters the throat, the compensator can advance the firing of tubes A and B to prevent a decrease of welding current and heat.

26-7. Lamp Signals for Full Heat.—Tube 15 is a neon glow lamp (center of Fig. 26C) that signals the operator when tubes A and B are firing so early that the entire voltage wave is already being used to produce welding heat. When tube 15 glows brightly, no further correction can be made by the compensator circuit, even though the tube-3 filament cools and "asks" for greater weld heat. When the main ignitron tubes are fired slightly later in their a-c half cycles, so that less than full heat is obtained at the weld, lamp 15 does not glow brightly. Lamp 15 is controlled by thyratron tube 5. The supply voltage for lighting lamp 15 comes from a 230-volt winding of $S12T$ (above lamp 15). During the half cycle when $S12T$ terminal 10 is more positive than 38, lamp 15 never glows; tube $4B$ acts as a rectifier and prevents electron flow through lamp 15 at this time. However, when terminal 38 is more positive than 10, electrons may pass through tube $4B$; lamp 15 glows if tube 5 is not passing current. (Electrons flow from 10, cathode to anode of tube $4B$, through lamp 15 and $32R$ to 38.) However, if thyratron 5 fires, the voltage between its anode 34 and cathode 10 drops to about 15 volts;* this is also the voltage across tube $4B$ and lamp 15, and it is not enough voltage to make lamp 15 glow brightly.† So, whenever tube 5 fires, lamp 15 has very little glow.

* Most of the $S12T$ voltage is now across $32R$.

† At the start of each cycle, a slight delay in firing tube 5 (as mentioned later) might let lamp 15 glow slightly; to prevent this, $15C$ and $39R$ are connected across lamp 15 and tube $4B$. Enough voltage cannot appear across lamp 15 to make it glow, until $15C$ has been charged (by electrons flowing through $39R$). This charging requires only 1/10 cycle, but it is long enough to let tube 5 fire first.

Tube 5 does not fire unless its control grid is raised by a voltage appearing across 13*C*. With no 13*C* voltage, the tube-5 control grid is at the potential of point 30; because of the voltage divider 14*R* and 15*R*, point 30 is about 30 volts more negative than cathode 10. To fire tube 5, we must produce a voltage across 13*C* that raises point 33 (nearest the tube-5 grid) nearly 30 volts more positive than point 30.

Capacitor 13*C* is charged by the a-c voltage produced by *S*12*T* (below tube 4*B* in Fig. 26*C*); this voltage appears across *S*12*T* at all times after the *TR* contact has closed. During that half cycle when the tube-5 anode is positive, the 60-volt *S*12*T* winding is also positive at its terminal 32, so electrons flow from its terminal 29, through the *S*6*T* winding to mid-point 30 and into 13*C*. When no welding current is flowing (and *S*6*T* produces no voltage), the *S*12*T* voltage forces these electrons to charge 13*C* during the entire half cycle; the potential at point 33 quickly rises high enough to fire tube 5 and prevent lamp 15 from glowing. (During the next half cycle, 13*C* is charged in the reverse direction, but this does not matter.)

When welding current flows, the voltage produced by the upper half of the *S*6*T* winding (between mid-point 30 and terminal 29) opposes the *S*12*T* voltage. This is shown in the lower center of Fig. 26*C*, where half cycle *U* is the *S*12*T* voltage, and *S*6*T* produces voltage *V*. Both of these are 60-volt waves, so the voltage *V* exactly matches voltage *U* at all parts of the half cycle, except at the gap. (During this gap, there is no flow of welding current; current has stopped flowing in one ignitron and has not yet started to flow in the other ignitron.) Since voltages *U* and *V* offset each other, there is no voltage left for charging capacitor 13*C*, except during the gap; the shaded part *W* is now the charging voltage. Here the width of *W* is $\frac{1}{8}$ of the half cycle or about $\frac{1}{1000}$ sec. This time is long enough to let voltage *W* force electrons through 30*R* to charge capacitor 13*C* to more than 30 volts, since the time constant[4-5] is only 0.0005 sec. As long as there is such a gap in the *V* voltage, capacitor 13*C* is charged enough to fire* tube 5.

* Notice that, owing to the natural shape of the welder-voltage wave *V*, tube 5 is not fired until after a delay *X*; this shows the need for 15*C* and 39*R*, as is explained in the previous footnote.

However, when the ignitrons are fired earlier, so that the full wave of voltage is being applied to the welder, the gap disappears from the $S6T$ voltage V. When this gap has almost disappeared, only the "sliver" of voltage Y remains. The time width of this Y voltage is less than the time constant (of $13C$ and $30R$); this charging voltage comes and goes before $13C$ can charge to enough voltage to fire tube 5.

This current-regulating compensator often may advance the firing of the ignitrons so that full heat is obtained. The tube-9 circuit[26-3] keeps both ignitrons firing so that the entire voltage wave is applied to the welder. Just as this full-heat point is reached, tube 5 fails to fire, so lamp 15 glows, to show that no greater heat may be obtained.

Questions

True or false? Explain why.

1. In Fig. 26A, if tube 5 is removed, tubes 4 and 6 stop glowing.

2. In Fig. 26A, if ignitron A fails to fire, this has no effect on the voltage across capacitor $9C$.

3. In Fig. 26A, if the leads are reversed to $P6T$, this has no effect on the operation of tube $9B$.

4. If $21R$ burns open (near tube 7 in Fig. 26A), the welding current increases.

5. The firing of tubes 7 and 8 (in Fig. 26A) makes transformer P produce all its voltage peaks in the same direction; however, if P is connected across an a-c voltage, its alternate peaks occur in opposite directions.

6. In Fig. 26C, if tube 3 is removed, (a) the $S7T$ voltage increases a large amount. (b) If a weld is now tried, it is too hot.

7. In Fig. 26C, if $4P$ is turned slowly, the $S6T$ voltage fires tubes 12 and 13 at various points in the half cycle.

8. In Fig. 26C, if one wire is disconnected from $P6T$, (a) there can be no flow of welding current. (b) If a weld is now tried, tube 15 glows.

9. In (b) of Fig. 26B, the tube-$9B$ circuit has no effect if voltage Y is 60 volts, equal to voltage Z.

10. In Fig. 26C, if tube 1 is removed, there will be no welding current.

CHAPTER 27

ELECTRONIC SERVICE INSTRUMENTS

Hundreds of kinds of electronic measuring devices are in use;* many books describe such instruments. Here we look at the circuits of only three instruments, such as are used in industry to service or check other electronic equipments and fast-moving objects. These instruments appear in Fig. 27*A*. Without an electronic voltmeter and an oscillograph,† good maintenance of most tube-operated equipment is very difficult.

Detailed instruction for the use of such instruments is not intended here; instead, let us study the circuits of these tube-operated instruments, to see how they can measure voltages and supply information far beyond the range of most electric instruments.

27-1. The Need for a Vacuum-tube Voltmeter.—Why get an electronic voltmeter, when you already have a d-c voltmeter?

Recently a plant electrician, trying to measure the d-c voltage supplied to tube circuits in a seam-welder control, found that he could not use his voltmeter, for the $\frac{1}{4}$-amp fuses in this d-c circuit blew open as soon as he connected the voltmeter. This old instrument needed too much current,‡ to move its pointer; connected across 300 volts d.c., it drew more than $\frac{1}{4}$ ampere.

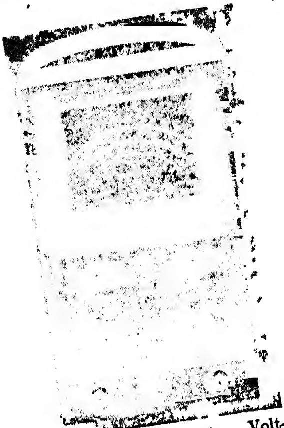
Ordinary voltmeters may draw 1 to 100 milliamperes when measuring 100 volts. While such meters may be good enough to measure power voltages, see what happens when they are used on electronic equipment having high-resistance circuits.

Suppose that your voltmeter draws 10 ma ($\frac{1}{100}$ ampere) when connected to 100 volts d.c. The resistance inside this voltmeter is 10,000 ohms (100 volts divided by $\frac{1}{100}$ ampere); this meter

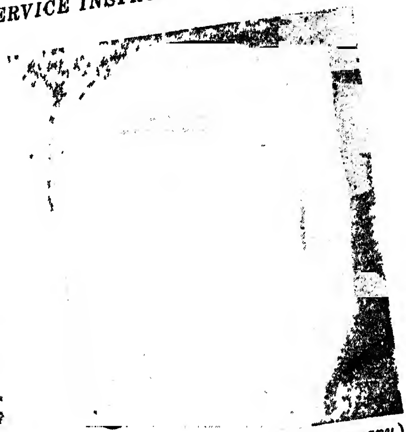
* Chapter 21 describes potentiometers, which are electronic instruments.

† The cathode-ray oscillograph, whose "picture tube" is watched as its picture changes, is often called an *oscilloscope*, or "scope."

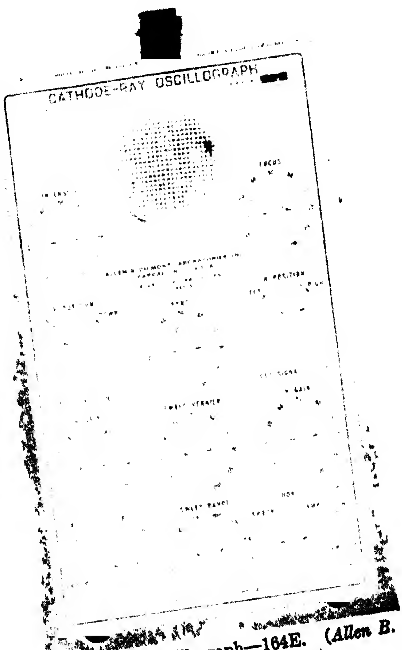
‡ Very few modern instruments need as much as $\frac{1}{10}$ of this amount of current.



Electronic voltmeter—Volt-Ohmyst 195 (*Radio Corporation of America.*)



Strobotac 631-B (*General Radio Company.*)



Cathode-ray oscillograph—164E. (*Allen B. DuMont Laboratories, Inc.*)

FIG. 27A.—Electronic service instruments.

is said to have 100 ohms per volt.* Now try to use it to measure any voltage in Fig. 27*B*.

The voltages shown in Fig. 27*B* are the true voltages when there is no tube-*C* current. If you connect your 100-ohms-per-volt meter between *A* and *B*, it will not show 90 volts; there will be less than 82 volts between *A* and *B*. The current drawn by the meter must pass through the 1000-ohm resistor 1*R*. At 82 volts, the meter draws 8.2 ma; this current causes 8.2 volts more drop across 1*R*, so that the *A*-to-*B* voltage becomes 90 − 8.2 or 81.8 volts.

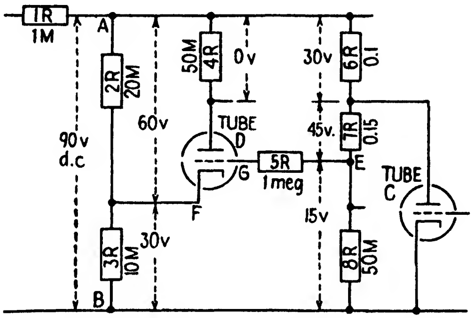


FIG. 27*B*.—What kind of voltmeter can measure the voltages of this circuit?

Now try again, using a better voltmeter, which is marked "2000 ohms per volt." If a 150-volt scale is being used, the meter now has 150 × 2000 or 300,000 ohms. Connected across 90 volts d.c., only $90/300{,}000$ or 0.0003 amp ($3/10$ ma) passes through the meter. When this meter measures the *A*-to-*B* voltage, the meter current causes only $1/4$ volt drop across 1*R*, a difference too small to be seen on the meter.

Next connect this meter from *E* to *B* to measure the voltage across resistor 8*R*. This reading is low on the 150-volt scale, so the 30-volt scale is used instead. At 2000 ohms per volt, the meter resistance is now 60,000 ohms. Since the meter is now in parallel with the 50,000 ohms of 8*R*, the total resistance between *B* and *E* is reduced nearly to 27,000 ohms, so the voltage across 8*R* drops to about 8 volts; the voltage increases across 6*R* and 7*R*. Such a meter cannot read the true circuit voltage, for the meter current changes the circuit voltage.

* If the meter has several voltage scales or connections, each scale may have a different value of ohms per volt.

Even the best of d-c voltmeters (having about 20,000 ohms per volt) cannot read the grid voltage of tube D, between grid G and cathode F. Figure 27B shows that G is 15 volts more negative than F (for there is no grid current or voltage across 5R). Using a 30-volt scale, the meter resistance is 600,000 ohms. When this meter is connected between G and F, this 0.6-megohm meter resistance is in series with the 1 megohm of 5R. The 15 volts between E and F is divided so that nearly 10 volts appears across 5R, and the voltmeter reads less than 5 volts from G to F. Also, since the grid of tube D is only 5 volts negative, tube D passes anode current; the meter disturbs the tube-D circuit.

In contrast, the electronic or vacuum-tube voltmeter connects the unknown voltage to the grid circuit of a high-vacuum tube. The tube grid draws no current from the measured circuit; a very small current may pass through a voltage divider inside the instrument. The instrument next described has an internal resistance of about 10 megohms, so it causes little or no disturbance when used to check most industrial electronic circuits.

27-2. An Electronic Voltmeter (RCA VoltOhmyst, Type 195).—The circuit of this instrument is shown in Fig. 27C. The main meter circuit is at the right; the circuits at the lower left include a voltage divider,[3-7] so that the meter pointer may be moved across the whole scale by only 5 volts, or by 10, 50, 100, 500 or 1000 volts as chosen by a range switch. The circuit near tube 4 is added, so that this instrument may measure a-c voltages; another circuit includes a 3-volt battery, so that this instrument may measure ohms and megohms.

This instrument operates from a 50-cycle or 60-cycle supply at 105 to 125 volts. Transformer windings (not shown) provide low voltage for all tube heaters. Tube 3 rectifies the a-c supply voltage; 1R and 1C filter this voltage so that about 86 volts d.c. appears between points 1 and 2.

This voltage is applied to a four-sided bridge circuit, with the meter connected between the corners 3 and 4. In this bridge 8R is equal to 9R, and tube 1 is like tube 2; 4R is equal to 5R. If the current flowing through tube 1 is exactly equal to the tube-2 current, the voltage from point 1 to 3 is equal to the voltage from point 1 to 4. Since 3 and 4 have the same potential, no current flows through 10R and the meter; the meter reads zero. However, if the tube-1 control-grid potential is raised so that

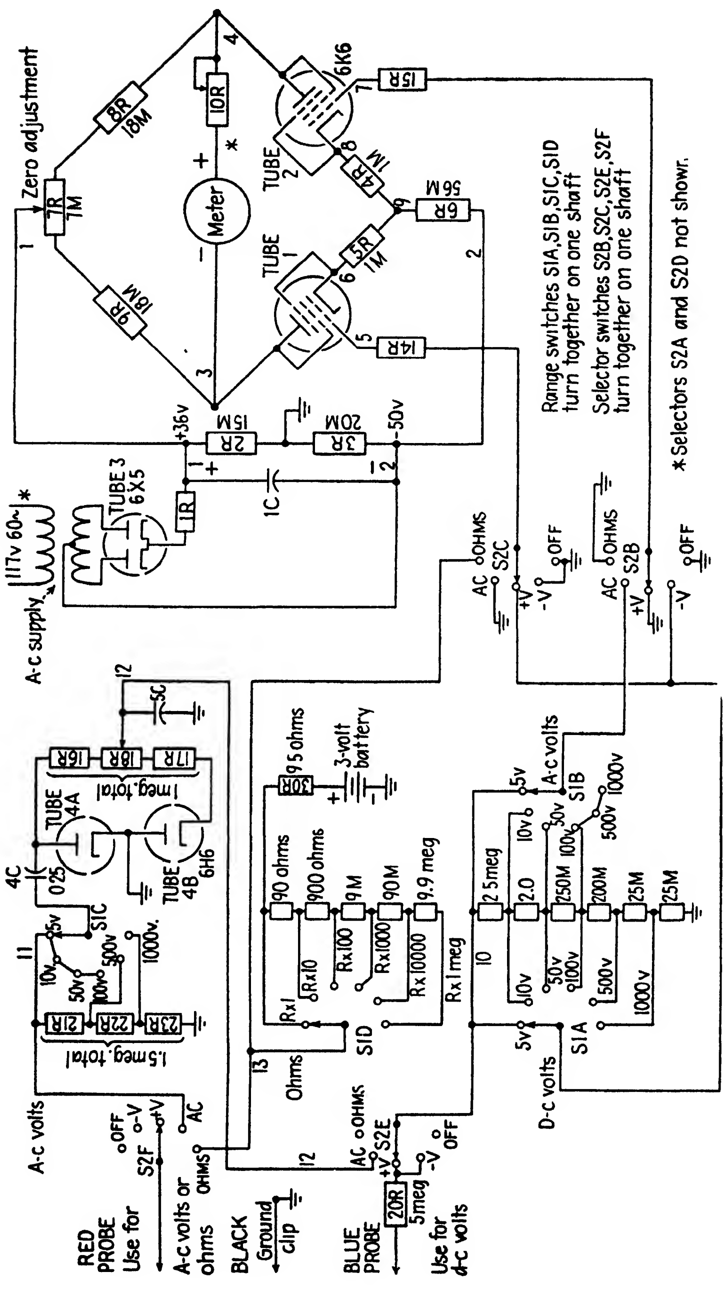


FIG. 27C.—Circuit of an electronic voltmeter (RCA VoltOhmyst, type 195).

tube 1 passes more current than tube 2, the increased voltage drop across $9R$ forces point 3 to a lower potential than point 4. Some of the electrons that flow from point 2 through $6R$, $5R$ and tube 1 now pass through the meter and $10R$ to point 4, through $8R$ and $7R$ to point 1. Since the meter needle moves across the whole scale when a current of only 200 microamperes (0.0002 amp) flows through the meter, point 3 needs to be only a small part of a volt below point 4; a tiny increase in the tube-1 current causes the meter reading.

The grid voltages 5 and 7 of tubes 1 and 2* are received through selector switch *S*2. This switch has five positions, to choose whether the meter is to measure "Ohms," "A-c volts," "+Volts" (d.c.), "−Volts" (d.c.), or to be in the "Off" position. All the contacts of this switch are moved by a single handle or dial; in Fig. 27*C* the contacts of *S*2*B*, *S*2*C*, *S*2*E* and *S*2*F* all connect to the "+V" terminal, so the meter is now set to measure the d-c voltage between ground (⏚) and a point more positive than ground. To bring this voltage to the instrument for measurement, the "D-c" pointed blue probe and the "Ground" black clip (at the left in Fig. 27*C*) are connected to the voltage. Notice that the ground clip is connected through switch *S*2*B* (lower center) to the grid of tube 2. The blue "D-c" probe (containing the high resistance $20R$) is connected through switches *S*2*E*, *S*1*A* and *S*2*C* to the grid of tube 1; the voltage being measured appears between the tube-1 grid and the tube-2 grid. When this voltage is 5 volts, the meter needle swings across the whole scale.

To measure 100 volts, range switch *S*1*A* is turned to the "100-volt" position. (At the same time, *S*1*B*, *S*1*C* and *S*1*D* turn also, but the voltages controlled by them are not being used while the selector is in the "−V" position.) The 100 volts d.c. is applied (between point 10 and ground) to the string of six resistors in the divider, but only 5 volts (appearing across the lower three resistors) is applied to the grid of tube 1. Now let us see how this grid voltage controls tubes 1 and 2.

Tubes 1 and 2 are connected with resistor $6R$ to act as a "long-tailed pair," as described in Sec. 16-5. The anode current of

* Tubes 1 and 2 are pentodes; since two grids of each tube are connected to anode and cathode, only the control grid (nearest the cathode) is used for controlling the anode current.

both tubes passes through $6R$. When the measured voltage is zero, both grids 5 and 7 are at ground potential; meanwhile, point 2 is 50 volts more negative than ground. Enough current flows through tubes 1 and 2 to produce more than 50 volts' drop across $6R$ so that cathodes 6 and 8 are more positive than grids 5 and 7. If the measured voltage increases, raising the tube-1 grid potential, more electrons flow through $6R$, $5R$ and tube 1. Since the increased drop across $6R$ raises the potential of point 9, cathode 8 of tube 2 rises also. (Meanwhile, the tube-2 grid remains at ground potential.) The tube-2 current decreases. We see that a more positive potential at tube-1 grid turns on tube 1 (lowering point 3) and turns off tube 2 (raising point 4); the voltage between points 3 and 4 forces current through the meter, so that its pointer moves upscale.

If the potential at the blue "D-c probe" is more negative than ground, the meter tries to "read backward." However, we may turn the selector switch to the "$-$V" position; $S2B$ now connects the blue probe to the grid of tube 2, while $S2C$ connects the tube-1 grid to ground. The measured negative potential decreases the tube-2 current (raising point 4); less current through $6R$ lowers the potential of point 9 and cathode 6, so the tube-1 current increases (lowering point 3). The meter now reads upscale as the measured voltage becomes more negative.

27-3. Measuring A-c Volts and Ohms.—When the selector switch $S2E$ is turned to the "AC" position, in Fig. 27C, the blue probe is not connected and cannot be used. The red probe is now connected, through selector $S2F$, range switch $S1C$ and capacitor $4C$, to the anode of tube $4A$. This tube circuit changes the measured a-c voltage into a d-c signal (as next described), which appears at point 12; $S2E$ connects this signal to point 10, so switches $S1B$ and $S2B$ apply a d-c voltage to the grid of tube 2. Meanwhile, the tube-1 grid is connected to ground. (These grid connections are like those used in the "$-$V" position; we may expect that the measured a-c voltage forces point 12 more negative than ground.)

During that half cycle* of a-c measured voltage when the red probe is more positive than the ground clip, electrons flow from ground, cathode to anode through tube $4A$ into capacitor $4C$,

* This instrument may be used to measure a-c voltages at frequencies from 30 to 100,000 cycles per second.

returning through $S1C$ and $S2F$ to the red probe. A half cycle later, electrons flow from the red probe into $4C$; then they must pass through the 1-megohm resistance of $16R$, $18R$ and $17R$, cathode to anode of tube $4B$, to ground. The electrons flow easily through tube $4A$ to charge $4C$ to the crest of the measured a-c voltage;* this charge makes the $4C$ right-hand terminal (nearest point 12) more negative. Little of this charge can be removed during the negative half cycle, since fewer electrons pass through the 1-megohm resistance. (The time constant of this resistance and $4C$ is $\frac{1}{4}$ sec, so the $4C$ voltage decreases very little during a half cycle.) Because of this switching action of tube 4 ($4A$ and $4B$ in the same tube), the charge on capacitor $4C$ keeps point 12 more negative than ground. This 12-to-ground voltage is filtered or smoothed by $5C$, so that its effect (through $S2E$ to point 10) is the same as a "$-$V" d-c voltage.

When the measured a-c voltage is zero, there is no charge on $4C$, so points 12 and 10 are at ground potential and the meter reading is zero. A-c voltages up to 100 are applied directly to tube 4; this larger 12-to-ground voltage is applied to the same divider (below point 10) as is used for d-c measurements, and $S1B$ applies part of this voltage to the tube-2 grid. When $S1C$ is turned to the 500- or 1000-volt position, only part of the a-c voltage across the divider ($21R$, $22R$, $23R$) is used for charging $4C$.

To measure resistance, the selector switch is turned to "Ohms." This measuring is done when the resistance circuit is disconnected from all electric power, so the electronic voltmeter includes a 3-volt battery (near the center of Fig. 27C) to supply a voltage for the tube-1 grid. From the negative or grounded terminal of this battery, electrons flow through the ground clip to the unknown resistance, returning through the red probe and $S2F$ to point 13, through $S1D$ and $30R$ to the positive battery terminal. Notice that $30R$ and the unknown resistance act as a voltage divider, which controls the potential at point 13; the voltage across the unknown is used to raise the point-13 potential, applied to the control grid of tube 1. (The tube-2 grid is at ground potential.) If the unknown resistance has less ohms than $30R$ (9.5 ohms),

* After $4C$ is charged by this a-c voltage, the instrument draws only enough current to restore the tiny amount lost during the negative half cycle, and also the current that passes through the 1.5-megohm voltage divider.

most of the 3 volts appears across $30R$. The rest appears across the unknown, and raises the tube-1 grid potential very little; the needle remains at a low-resistance reading. If the unknown is much greater than $30R$, nearly the entire 3 volts appears across the unknown, and raises the tube-1 grid so that the meter needle swings up to a higher resistance reading. If $S1D$ is turned to the "R × 100" position, the unknown resistance is now in series with about 1000 ohms; if the unknown resistance is also about 1000 ohms, the meter needle rests halfway up-scale, at the 10-ohm mark.* To measure a very large resistance, $S1D$ may connect about 10 megohms in series with the unknown; the meter scale now reads directly in megohms.

27-4. The Cathode-ray Tube.—A cathode-ray oscillograph is an instrument (shown in Fig. 27*A*) that includes a cathode-ray tube instead of a meter. Such an instrument is used as a voltmeter;† the measured voltage moves a spot of light, seen at the end of the tube, instead of moving a needle or a pointer. Since this spot of light can move much faster than a pointer, the oscillograph shows quick changes of voltage; it traces curve pictures on the end of the tube that show how a circuit acts within a small part of a second.

The working parts of a cathode-ray tube are shown in Fig. 27*D* and again at the lower right in Fig. 27*E*. This tube is nearly 12 inches long; narrow at one end, it widens at the other end to a circle 3 inches across. The bright spot or "picture" is seen in this circle, so this end of the tube appears at the front of the oscillograph (as shown in Fig. 27*A*).

Many different voltages are connected to the tube to make it work. Figure 27*D* shows that this high-vacuum cathode-ray tube has a filament, a heated cathode, a control grid and an anode; so far, this tube is merely a pliotron (described in Sec. 7-4). It has also a second anode and two pairs of deflecting plates.

Electrons from the heated cathode are attracted toward both anodes. The second anode is 1100 volts more positive than the cathode, so the electrons reach such high speed that most of

* This 10-ohm reading on the meter scale must be multiplied by 100, since $S1D$ is set at "R × 100".

† This applies to the type of tube described here. Some cathode-ray tubes use coils outside to move the electron beam; such a tube responds to current in the coils and is used like an ammeter.

them shoot past the anode and strike the circle end of the cathode-ray tube. The inside of this glass tube circle or screen is coated with a fluorescent "paint," which glows when the electrons strike it at high speed.* Instead of letting the electrons scatter over a large portion of this painted end, the first anode bends the paths of the electrons so that they all strike at one tiny spot on the tube end, or screen. This focusing of the beam of electrons is adjusted by a slight change of potential at the first anode, which acts like a screen grid.

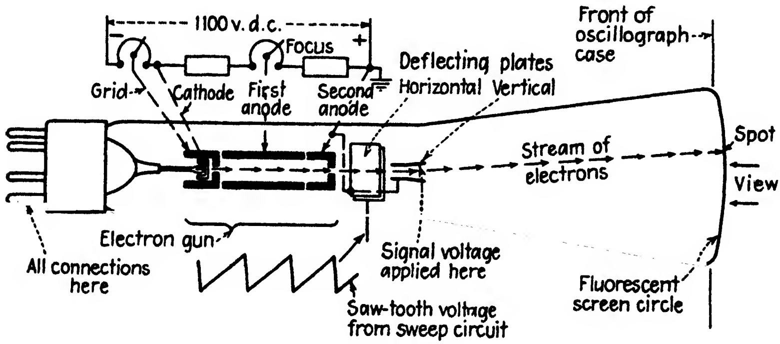


FIG. 27*D*.—Parts of a cathode-ray tube and their connections.

Here the cathode, control grid and two anodes act as an *electron gun;* together they "shoot" a narrow stream† of electrons toward the target, or screen. After leaving this gun, the stream of electrons may be controlled or bent by the voltage connected to either pair of deflecting plates, as a bullet's direction may be changed by the wind or by gravity. Since the electrons have a negative charge, the electron stream is attracted or bent toward a deflecting plate that is more positive.‡ By making that deflecting plate more negative, the stream is repelled so that it strikes the screen at a different spot. (Usually one plate of each pair is

* Fluorescent lights also glow when electrons strike such a "paint" on the inside wall of the glass tube.

† The grid is a solid piece of metal with one small hole, which is the only path by which electrons may pass toward the anodes. The second anode also has a small hole, which aims the electrons between the deflecting plates. Similar electron guns are used in television tubes and in the electron microscope.

‡ A magnet held near the tube will also bend the electron stream and move the bright spot.

held at ground potential.) So, by changing the potential of a deflecting plate inside the tube, the bright spot is moved across the face of the tube screen.

Many lines or curves may appear on the screen at the same time; all these curves are made by the same spot, or electron beam, which moves back and forth across the screen so many times each second that your eye sees all these movements at once. The "paint" used on most cathode-ray-tube screens holds the bright marks for perhaps 1/10 sec after the electron beam has passed; this helps to produce a steady picture or curve, without flicker. After the electrons strike the screen, they return (to ground) through a circuit "painted" inside the glass of the tube.

The oscillograph, whose circuit is studied later, furnishes all the voltages needed by the cathode-ray tube. Two wires from the oscillograph are connected to the voltage you wish to measure; the oscillograph applies this voltage to one pair of deflecting plates inside the tube. This is usually the "Vertical" pair of plates; any voltage at these plates makes the bright spot move up or down on the screen. A voltage at the other, or "Horizontal," pair of deflecting plates makes the spot move to the left or to the right. By combining these up-and-down and sidewise movements, the bright spot traces the curve of the voltage that is being measured.

When no voltage is applied to either pair of deflecting plates, a single bright spot is seen on the screen.* If only the vertical plates receive voltage, the spot traces a straight line up and down on the screen. The height of this line increases if the measured voltage increases. Rapid changes in this voltage cannot be seen unless the bright spot is moved from left to right at the same time. This sidewise movement is produced by a "sweep circuit" inside the oscillograph, which makes and applies a special voltage to the "horizontal" plates. This special voltage has a "saw-tooth" waveshape, shown in Fig. 27*D*; this voltage gradually makes one of the horizontal plates more positive, so that the bright spot moves slowly† from left to right; in this way, any sudden changes

* The tube may be damaged if this bright spot remains still for a long time.

† This movement is too fast for your eye to follow. When the oscillograph shows a single wave of 60-cycle voltage on the screen, the bright spot moves from left to right in 1/60 sec, but comes back, right to left, in about five-millionths sec.

in vertical or measured voltage appear as breaks in a curve. When the bright spot reaches the right-hand side of the screen, it returns very quickly to the left-hand side, to start another left-to-right movement.

27-5. A Cathode-ray Oscillograph (DuMont Type 164E).— Figure 27*E* shows the circuit of this oscillograph, which operates the cathode-ray tube 6 at the right. At the left, tubes 1 and 2 rectify a-c power so that 400 volts d.c. appears between point 1 and ground bus 2, while 1100 volts d.c. appears between 2 and point 3 and is applied to the electron gun, as shown in Fig. 27*D*.

Connection terminals on the front of the oscillograph are shown as small circles in Fig. 27*E*. Between terminals *V* and *G* we connect the voltage whose waveshape we wish to watch on the screen. Before we connect this voltage or see how it is changed into a curve on the screen, let us learn how to adjust the bright spot on the cathode-ray tube.

After the oscillograph connection cord is plugged into a 115-volt a-c outlet, the "Intensity" dial switch 1*R* (at the bottom of Fig. 27*E*) is turned, to close the circuit to the supply transformer. After about 20 sec, the tubes become heated; then, as 1*R* is turned further (clockwise), the green* spot may appear in the tube-6 circle on the front of the oscillograph. This turning of 1*R* raises the tube-6 grid potential, so that more electrons pass the grid, rush toward the anode, and strike the screen; turning 1*R* can dim the spot and make it disappear, entirely by grid control. The spot may be ¼ inch across; turning 2*R* will focus this spot† to a small bright point.

At first, the spot may appear anywhere on the screen circle, or it may be off the screen, out of sight. However, turning 3*R*, "V-Position," moves the spot up or down, while 4*R*, "H-Position," moves the spot to left or to right. Notice that one deflecting plate of each pair is connected to the second anode and to ground; the other "horizontal" plate is connected to terminal *H*, and through 16*R* to the slider of 4*R*. Also, the other "verti-

* Some cathode-ray tubes show a blue or a white spot, depending on the kind of fluorescent paint used on the screen.

† Notice that the first anode, connected to 2*R*, is at a potential lower than the second anode. This voltage between these anodes (helped by the shape and position of the first anode) makes all parts of the stream of electrons come together at the screen. Turning 2*R* adjusts this focusing voltage.

cal" plate is connected through 15*R* to the slider of 3*R*. By the turning of 3*R* or 4*R*, the deflecting-plate potential can be made more positive (near the point-8 end) or more negative than ground, so that the plate either repels or attracts the electron stream and controls the position of the bright spot on the screen. Later, when voltage signals are brought through capacitors 9*C* and 11*C* to these deflecting plates, the resulting curve may be moved as a whole on the screen by 3*R* and 4*R*.

The *H* and *V* terminals (at the right in Fig. 27*E*) are on the back of the oscillograph. By the removal of small wires here, the deflecting plates may be disconnected from the oscillograph circuits;* if test voltages are then connected between plate terminals *H* or *V* and ground, these voltages directly move the spot on the screen (about 1 inch for each 30 volts applied).

27-6. Amplifiers in the Oscillograph.—To let you watch the waveshape of small voltages, amplifier circuits are included in the oscillograph. A pair of outside wires brings the voltage to terminals *V* and *G* (near the left-hand side of Fig. 27*E*); this a-c voltage now appears across 5*R*. With the 5*R* slider turned clockwise, less than 1 volt (applied between *V* and *G*) makes the bright spot move 1 inch up or down on the screen. This is a gain[7-6] of more than 30, since 30 volts (directly on the deflecting plate) is needed to move the spot 1 inch.

This voltage at 5*R* slider is applied to the control grid of tube 3, so that this grid swings above and below the ground potential *G*. This changes the amount of tube-3 anode current; these electrons flow from ground 2 through 12*R*,† tube 3, 17*R* and 2*X*

* The main oscillograph circuits can apply only a-c or changing voltages to the deflecting plates; such signals must pass through capacitors 11*C* and 9*C*. If the tested voltage includes any d-c voltage, this d-c portion will not be shown in the wave on the screen. For checking industrial electronic circuits, we often need a "scope" that shows d-c as well as a-c voltages. In Fig. 27*E*, we gain this result by removing the wire jumper above plate-terminal *V*; *V* may then be connected to the slider of a 5-megohm potentiometer. When one side of this potentiometer is connected to ground, the other side is connected (through a protective fuse and resistor) to the voltage to be tested. Such changes to oscillographs are described by B. L. Weller in Servicing Resistance Welding Controls, *Electronics*, January, 1943.

† The voltage drop across 12*R* charges 21*C* so that the tube-3 cathode remains several volts more positive than ground; this 21*C* voltage is the negative grid bias for tube 3.

to positive point 1. When the tested voltage drives the tube-3 grid more negative, current decreases in tube 3 and 17*R*; the point-4 potential rises, making the *V* deflecting plate more positive.

When the tested voltage is 150 volts,* the 5*R* slider is turned down so that a very small part if this voltage reaches the tube-3 grid; in this way, the "*V*-gain" is decreased, and the bright spot or wave is kept inside the screen circle.

Near the center of Fig. 27*E*, if switch 2*S* connects terminal *H* to 10*C*, an outside voltage may be connected between *H* and *G*, to control tube 4 and the point-6 potential, applied to the "Horizontal" deflecting plate. However, for most service or tests on industrial equipment, 2*S* is turned to "Sweep," so that tube 4 is controlled by the changes of potential at point 5.

27-7. The Sweep Circuit.—To move, or "sweep," the bright spot from left to right across the screen so that we can see the rapid vertical changes of tested voltage, the circuit around tube 5 is used. Tube 5 is a small thyratron, as described in Sec. 11-2. Let us watch its action, as if in slow motion.

The 400-volt d-c supply (at the left in Fig. 27*E*) forces electrons to flow from grounded point 2 through 24*R* to point 7, and through 25*R* to positive point 1; this keeps the tube-5 cathode at least 4 volts above ground potential. (Meanwhile, turn 8*R* until the tube-5 grid is at gound potential.) Electrons flow through 24*R* also to charge capacitor 14*C* (or other capacitors connected by "Frequency" tap switch 4*S*), then through 4*S*, 26*R* and 7*R* to point 1.

When 14*C* first starts to charge, there is little voltage across 14*C*; there is not enough voltage 5-to-7 to fire tube 5. The potential at point 5 is low, so the tube-4 grid prevents much tube-4 current; the point-6 potential is high and keeps the bright spot at the far left on the cathode-ray-tube screen. However, as the electron flow gradually charges 14*C*, the point-5 potential

* Each oscillograph has an upper voltage limit, such as 100 or 250 volts a.c. To see the waveshape of higher voltages, connect five 25,000-ohm (or higher) resistors in series across the voltage; the voltage across the center resistor may then be within the safe range of the oscillograph.

Since one side of the tested voltage is connected to the *G* terminal, which is connected to the outer case of the oscillograph, the oscillograph should be on a wooden table; while it is connected to a high voltage, its case must not be touched.

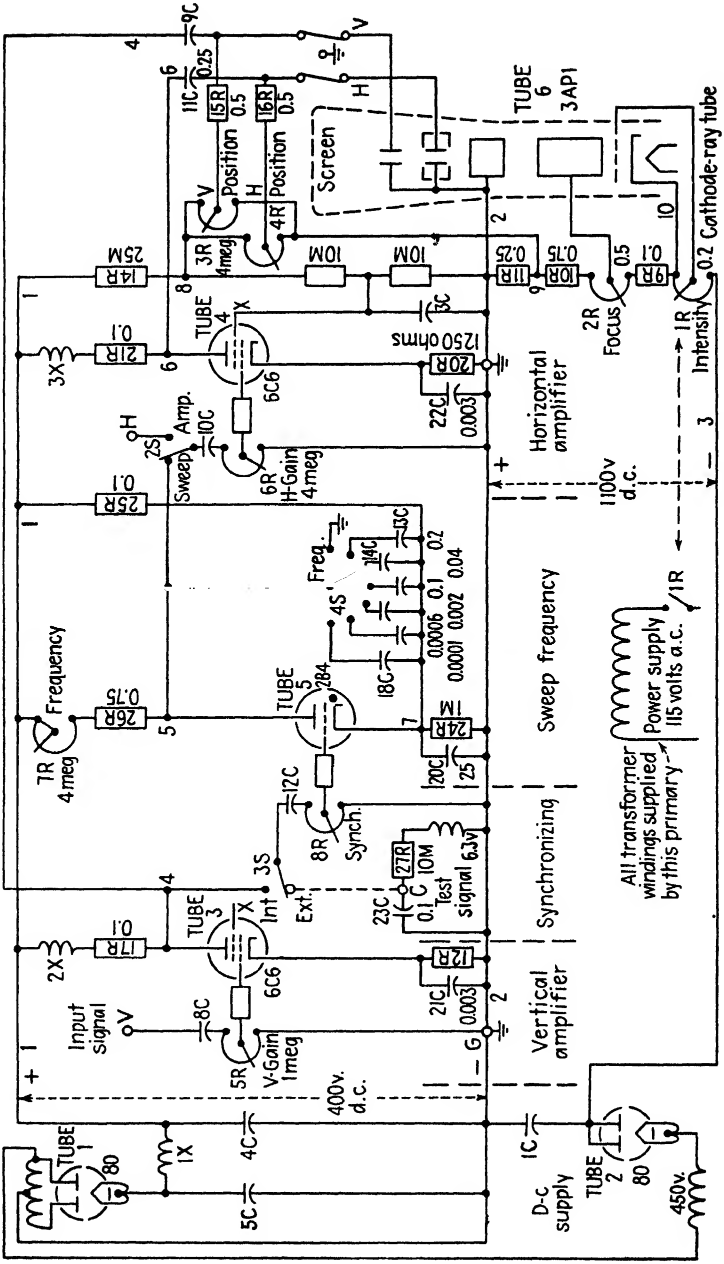


FIG. 27E.—Circuit of a cathode-ray oscillograph (DuMont type 164E).

rises steadily; the tube-4 current increases, steadily lowering the point-6 potential so that the bright spot moves toward the right across the screen.*

When the 14*C* voltage becomes large enough (20 to 40 volts), tube 5 suddenly fires, letting 14*C* discharge almost instantly. (Electrons flow from 14*C*-terminal 7, through tube 5 and the switch 4*S* to the upper terminal of 14*C*.) . Point 5 drops suddenly to the potential of point 7, so the tube-4 current drops; the potential of point 6 rises so quickly that the bright spot returns across the screen (from right to left) faster than the eye can follow. Since capacitor 14*C* is discharged, there is no voltage 5-to-7, and the tube-5 current stops; 14*C* then starts to charge, again making the bright spot sweep across the screen. By this slow-charge—fast-discharge action,† 14*C* and tube 5 make the point-5 potential follow the saw-tooth waveshape (shown in Fig. 27*D*) needed for the sweep circuit.

If a 60-cycle voltage wave is being applied to the vertical plates (through *V*, tube 3 and point 4 as described above), a single 1-cycle wave will appear and stand still on the screen if tube 5 is fired exactly 60 times each second. The size of 14*C* is chosen so that, after adjusting the amount of resistor 7*R*, the 14*C* voltage rises and fires tube 560 times each second.‡

27-8. Synchronizing the Wave.—No matter how carefully 7*R* is controlled, the position of the curve may move slowly across the screen. To hold this curve still, tube 5 may be fired by changing its grid potential; to do this, the tube-5 grid is connected to a voltage that is in step with the curve on the screen. This is called *synchronizing* the wave.

Near tube 3 in Fig. 27*E* is a switch 3*S*. When 3*S* is thrown to the "Internal" position, the changing voltage between point 4 and ground is now applied across 8*R*. After 7*R* has been set so that the curve moves very little on the screen, the 8*R* slider is turned up (clockwise) so that more of the 4-to-ground voltage reaches the tube-5 grid; this "locks" the wave, to hold it still.

* In some oscillographs the spot sweeps toward the left and returns suddenly left to right.

† Here tube 5 acts as an inverter, as described in Sec. 20-1.

‡ If tube 5 fires a bit too often, the 1-cycle wave moves toward the right across the screen and may cause many waves to appear at the same time; if the 7*R* resistance is increased to that 14*C* charges more slowly and tube 5 fires less often, the 1-cycle wave may move to the left.

Each time point 4 rises, the tube-5 grid also rises. Tube 5 is fired always at this one point in the wave, so the curve on the screen always starts at the same point on the wave; the curve "stands still."

If you wish to see three or four waves of the 60-cycle voltage on the screen at one time, switch $4S$ is turned to connect $13C$ into circuit in place of $14C$. This larger capacitor takes more time to charge, so tube 5 fires less often; by the adjusting of $7R$, three, four or five waves can appear side by side on the screen.* Because of the synchronizing voltage from point 4, the picture changes suddenly from three waves to four waves as $7R$ is turned.

When testing 50- or 60-cycle circuits, it is better to synchronize the wave on the screen by setting $3S$ to the "External" position, and by making a wire connection between the "Ext" and "C" terminals (as shown by the broken line in Fig. 27E). This C terminal provides a test-signal voltage; a 6.3-volt transformer winding furnishes voltage through $27R$ and $23C$ so that 6.3 volts at 60 cycles† appears between C and G. When this 6.3-volt a-c signal is connected across $8R$, tube 5 may be fired in step with this 60-cycle signal. This is useful also when the vertical plate is disconnected from the tube-3 circuit, and receives its voltage directly (as is mentioned in Sec. 27-5, footnote).

27-9. A Stroboscope (General Radio Company Strobotac Type 631-B).—When this instrument shines its flickering light on an object that is turning or vibrating at high speed, that object may appear to be standing still or moving slowly. As shown in Fig. 27A, this stroboscope has a neon tube that gives a very short flash of light; its electronic circuit can make this light flash 14,400 times per minute. A dial is turned to adjust this flashing rate to as low as 600 per minute. When this light makes a fast-

* In other positions, $4S$ connects smaller capacitors into circuit, so that tube 5 fires hundreds or thousands of times per second. These high sweep speeds are used with high-frequency waves (such as are found in radio circuits). If tube 5 fires 300 times per second, a 60-cycle voltage (applied between V and G) appears on the screen as five waves crossing each other, for the bright spot passes across the screen five times while the 60-cycle wave is changing through one cycle.

† This test signal may be used (by a wire connecting terminals C and V) to check the operation of tube 3. If the oscillograph is supplied from 115 volts, 50 cycles, the 6.3-volt test signal is also a 50-cycle voltage.

turning motor appear to stand still, then the light is flashing once* each time the motor turns; since the dial is marked to show how often the light is flashing, it also shows the motor speed.

The circuit in Fig. 27*F* shows that the 115-volt a-c supply is rectified by tube 1 and filtered by 8*C*, 21*R* and 9*C* so that about 250 volts d.c. appears between points 1 and 4. At the right, the neon tube 3 produces the flashes of light; tube 3 is a cold-cathode thyratron which does not fire until its control grid 11 is driven about 100 volts more negative than its screen grid 12, so that a glow starts between these two grids.† When fired, the tube-3 current flows until its anode voltage (5 to 4) decreases to less than 60 volts. If the light flash (caused by this current) lasts more than a microsecond, the fast-turning object moves far enough during the flash to be blurred. Let us see how a short-time flash is produced. Turn the selector dial‡ to a high-speed position, so that the 1*S* contact opens, disconnecting 2*C*.

Above tube 3, capacitor 1*C* is charged by electrons flowing from negative point 4 into 1*C*, then through 1*R* to positive point 1. Resistor 1*R* has 3000 ohms, so 1*C* charges in less than $\frac{1}{100}$ sec and full d-c voltage appears across tube 3. When grid 11 is driven more negative for an instant (as described later), tube 3 passes current. Capacitor 1*C* discharges through tube 3 almost instantly. Since there are no resistors in this discharge path, the discharge current is large (causing the bright flash in tube 3); 1*C* discharges so quickly that the flash lasts less than a microsecond. At once 1*C* recharges, to be ready when grid 11 again fires tube 3.

Usually tube 3 is fired rapidly by tube 2 acting as an oscillator. Before watching this action, notice how tube 3 can be fired by a contactor outside the instrument; the selector dial is turned to "Contactor" position, moving the switch-2*S* contact (shown near the center of Fig. 27*F*) to the right. Such an outside contactor

* The motor also appears still if the light flashes once for each two turns of the motor. If the light flashes twice for each turn of the motor, you see the motor in two positions; every second flash shows the motor at the half-turn position. Select the highest flashing rate that shows the motor in only one position.

† GERMESHAUSEN, K. J., and H. E. EDGERTON: The Strobotron, *Electronics*, p. 12, Feb., 1937.

‡ The selector dial has six positions (shown in Fig. 27*A*, but not in Fig. 27*F*). This one dial moves the contacts of 1*S*, 2*S*, 3*S* and 4*S*.

may be driven from the shaft of a motor whose motion is being studied; although the motor speed may change, each turn of the motor flashes tube 3 once.

While the outside contactor is open, there is no electron flow through 18*R*, and capacitor 10*C* is charged to the voltage between points 8 and 4. Control grid 11 is at cathode-4 potential, and screen grid 12 is about 60 volts above 4; this amount of voltage between grids 11 and 12 is not enough to fire tube 3.

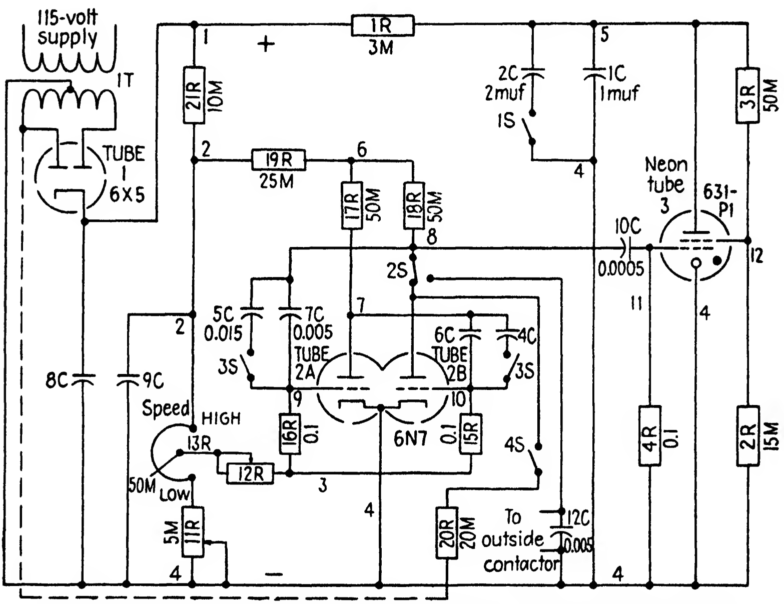


FIG. 27*F*.—Circuit of a Strobotac (General Radio Company type 631-B).

Each time the contactor closes, point 8 is suddenly lowered to point-4 potential. As capacitor 10*C* discharges, it forces current through 4*R*, so that grid 11 is forced more negative than 4. Grid 11 reaches a potential more than 100 volts below that of screen grid 12; this voltage starts a tiny arc or glow between 11 and 12, which fires tube 3. An instant later, when 10*C* has discharged and current through 4*R* stops, grid 11 is back at cathode-4 potential. Tube 3 cannot fire again until the outside contact opens and recloses.

27-10. Timing the Flashes.—Tube 3 may be flashed by the action of tubes 2*A* and 2*B* in Fig. 27*F*. (The two triodes 2*A* and

2*B* are in one tube.) Before contact 2*S* connects point 8 to the anode of tube 2*B*, notice that tube 2*A* is passing anode current; electrons flow from cathode 4 to anode 7, through 17*R*, 19*R* and 21*R* to point 1. Both grids 9 and 10 are slightly more positive than cathode 4. As shown at the left in Fig. 27*G*, point 8 is at high potential, but anode 7 is at low potential because of the voltage drop across 17*R* caused by the flow of tube-2*A* current.

As soon as 2*S* connects point 8 to tube 2*B*, electrons flow through tube 2*B*, 18*R*, 19*R* and 21*R* to point 1. The voltage drop

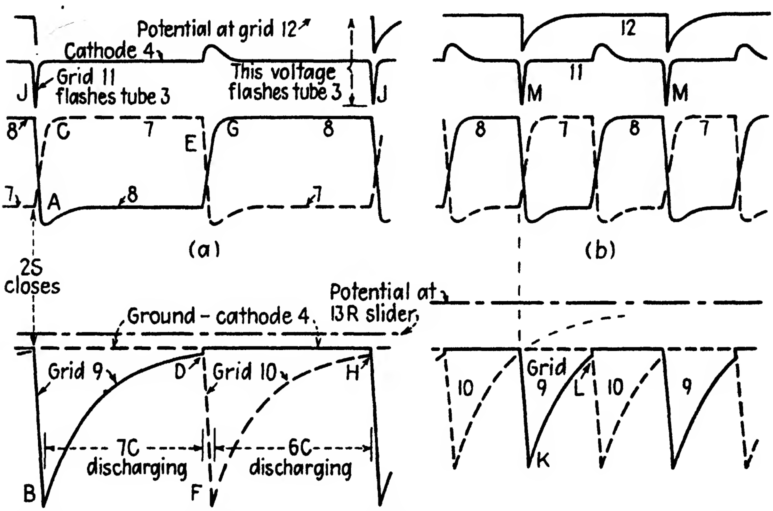


FIG. 27*G*.—Timing of light flashes controlled by multivibrator action (of tube 2 in Fig. 27*F*).

across these resistors forces point 8 to a lower potential (as shown at *A* in Fig. 27*G*) and flashes tube 3 as described above. The 8-to-3 voltage decreases, so capacitor 7*C* tries to discharge to this lower voltage;* electrons flow from point 9 through 16*R*, 12*R* and 13*R* to point 2, through 19*R* and 18*R* to 7*C*. The voltage drop across 16*R* forces grid 9 far below point 3 and cathode 4 (as shown at *B*); this reduces the tube-2*A* current quickly so that point 7 rises (at *C*). Now there is a delay until 7*C* has discharged enough to let grid 9 rise close to cathode 4. At *D*, tube 2*A* again passes current, lowering point 7 (at *E*). The 7-to-3 voltage

* Keep the selector dial in a high-speed position, so that the 3*S* contacts are open; 4*C* and 5*C* are not in circuit.

decreases, so capacitor 6*C* starts to discharge to this lower voltage; electrons flow from point 10 through 15*R*, 12*R*, 13*R*, 19*R* and 17*R* to 6*C*. The voltage drop across 15*R* forces grid 10 far below cathode 4 (as shown at *F*); this reduces the tube-2*B* current quickly, so that point 8 rises (at *G*). Now there is a delay until 6*C* has discharged enough to let grid 10 rise close to cathode 4. At *H*, tube 2*B* again passes current, the grid-11 potential drops and tube 3 flashes; all these actions are repeated.*

Part (*a*) of Fig. 27*G* shows circuit voltage waves when the speed dial 13*R* is near the low-speed end of its range;† the 13*R* slider is not far above the ground potential of cathode 4. The time delay caused by 7*C* and 6*C* lets the impulses *J* occur far apart, so as to fire tube 3 less often. However, in (*b*) the 13*R* slider has been moved to a higher speed part of its range, and the 13*R* slider is at a higher potential above ground. Now, when the point-8 potential drops (owing to tube-2*B* current), grid 9 is forced more negative than the 13*R* slider, as before; 7*C* discharges at the same rate as before. However, at *L* the grid-9 potential comes near the cathode-4 potential, so tube 2*A* passes current earlier. The dips *M* occur closer together and fire tube 3 at a faster rate.

With the selector dial in the "Strobotac High" position, 13*R* controls the flashing speed from 14,400 down to 2400 times per minute. For lower speeds, turn the selector to the "Strobotac Low" position; this closes contacts 1*S* and 3*S* in Fig. 27*F*. This connects capacitor 5*C* to 7*C* so that the time delay of "7*C* discharging" becomes four times as long (compared with 7*C* alone); also, 4*C* is in parallel with 6*C*, so that the grid-10 potential rises more slowly than before.

At these lower flashing speeds, contact 1*S* adds capacitor 2*C* to 1*C*. The added charge in 2*C* causes a longer flash of light each time tube 3 fires; although flashing less often, this longer flash

* A circuit like that of tube 2 in Fig. 27*F* is also called a *multivibrator*. Notice its "suicide" or snap action; as grid 9 rises above cutoff,[3-11] the start of tube-2*A* current lowers point 7 and grid 10 slightly. This decreases the tube-2*B* current so that point 8 rises, giving a further and more sudden rise at grid 9, to speed the turn-on of tube 2*A*.

† If the selector dial is at the "Strobotac Low" position, tube 3 flashes about 600 to 900 times per minute, at the low-speed end of the 13*R* dial. In the "Strobotac High" position, tube 3 flashes four times as fast. The curves in Fig. 27*G* apply to either of these selector positions.

helps to shine as much total light on the moving object as is given in the high-speed range.

The sliders on 11*R* and 12*R* adjust the flashing rate at 900 and 3600 (on 60-cycle supply), with the help of a vibrating reed (not shown) driven from a low-voltage transformer-1*T* winding; the light from tube 3 shines on this reed, which "stands still" when the light flashes exactly 900 or 3600 times per minute.

Tube 3 flashes exactly in step with the power-supply frequency, if the selector dial is turned to the "Line" position; this closes contact 4*S*, so that voltage from transformer 1*T* is applied through 20*R* to point 8. Each downward swing of this voltage fires tube 3, giving 3600 flashes per minute (on 60-cycle supply).

Questions

1. In Fig. 27*E*, which dials can change the height of an a-c wave on the tube screen?

2. In Fig. 27*F*, list five important timing combinations[4-5] of *R* and *C* (while the selector is in a "High" position).

True or false? Explain why.

3. When measuring a d-c voltage with the instrument of Fig. 27*C*, the only current drawn from this voltage is the current flowing through the divider (point 10 to ground).

4. When measuring ohms in Fig. 27*C* (with *S*1*D* set at R × 1), greater current is drawn from the battery when the meter pointer is moved upscale (reading higher ohms).

5. When reading 300 volts with the instrument of Fig. 27*C*, more current flows through the meter than when reading 3 volts.

6. If 30 volts d.c., applied at the *V* deflecting plates of a cathode-ray tube, will move the bright spot 1 inch away from center, 30 volts a.c. will move the spot much more than 1 inch from center.

7. The position of the bright spot (on the screen of the instrument of Fig. 27*E*) can be moved only by a change of potential at the deflecting plates.

8. With the oscillograph of Fig. 27*E* set for "Internal" synchronizing, an a-c wave on the screen reverses, or becomes upside down, when the wires from the measured a-c voltage are reversed at *V* and *G*.

9. If a broken contact in Fig. 27*F* prevents 3*S* from connecting 5*C* to 7*C*, while 4*C* is connected to 6*C*, the flashes of tube 3 are still equally spaced.

CHAPTER 28

NONELECTRONIC DEVICES

Today many of the electronic circuits used in industry include devices that are not electronic, but that add greatly to the successful operation of the circuit. Some of these nonelectronic devices are described briefly here.

28-1. Tachometer Generator.—In much the same way as a speedometer moves a pointer to indicate the speed of a car, the tachometer generator produces a voltage that shows how fast its own rotor is turning. For example, such a generator may produce 50 volts when turning 1,000 rpm and 150 volts at 3000 rpm. When tube-operated circuits are used to control or regulate the speed of a rotating unit, and that unit mechanically drives such a

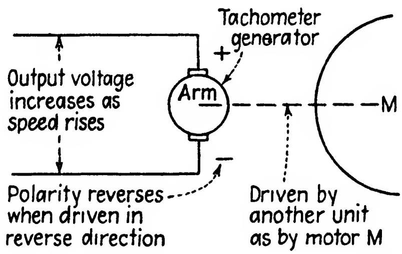


FIG. 28A.—Tachometer-generator voltage shows speed and direction of turning.

"tac" generator, the "tac" furnishes the electrical signal that "tells" the electronic circuit how fast the unit is turning.

This tachometer is an ordinary d-c generator,[17-1] in that it has a rotating armature with commutator and brushes (as shown in Fig. 28A); its field strength is kept constant, for it is furnished by permanent magnets (not requiring any field winding or wire connections). Since the "tac" supplies mainly a voltage, with very small current flow (if any), it is quite small.

28-2. Amplidyne.*—This d-c rotating unit may be either a motor or a generator. Its armature[15-1] is like that of an ordinary

* ALEXANDERSON, E. F. W., M. A. EDWARDS, and K. K. BOWMAN, The Amplidyne Generator, *General Electric Review*, March, 1940; MOHLER, F.,

d-c motor. It is usually a two-pole machine, but its nonmoving part has its windings distributed in slots. If four brushes are used, two of these are shorted, or connected together, as shown in the amplidyne generator in Fig. 28C.

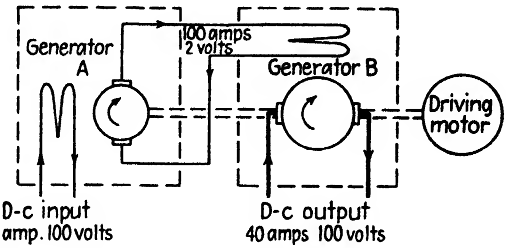


FIG. 28B.—Field current of one generator may control large output from a second generator.

An amplidyne acts much like an ordinary d-c machine; when it is used as a generator, its output voltage increases when you increase its field* current; as a motor, its speed increases when you decrease its field current. The advantage of the amplidyne is that much smaller field currents are needed; with only 30 to 100 ma (0.03 to 0.1 ampere) input to its field winding you may control 10 to 200 amperes output from its armature circuit. A

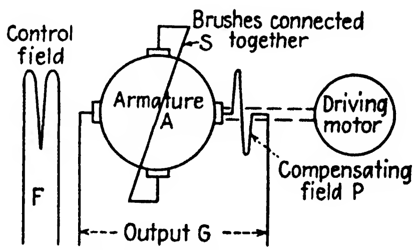


FIG. 28C.—Connections of an amplidyne generator.

similar increase of current is obtained when two ordinary d-c generators are connected as shown in Fig. 28B. Here a 10-watt input signal at the field of generator A controls 4000 watts' output from generator B; however, such a combination of two separate generators is slow to respond when the input signal changes.

The Amplidyne—A New Tool of Many Uses, *Iron and Steel Engineer*, September, 1940; FELIX, F., What is the Amplidyne? *General Electric Review*, August, 1943.

* This refers to a control field.

The amplidyne of Fig. 28*C* combines these two generators into one machine; very small current in winding *F* causes the turning armature *A* to generate a large current in the short-circuit connection *S*; this current in *S* causes the armature *A* to generate current at higher voltage in the output winding *G*. The watts' output *G* may be 2000 to 25,000 times as large as watts' input *F*. Of special importance, a signal change at *F* causes the output *G* to change very quickly. Since its speed of response is so much faster than that of an ordinary d-c machine, the amplidyne combines well with the speed of tube-operated circuits. Since currents of 100 ma are easily controlled by certain high-vacuum tubes,[7-10] we may use sensitive electronic circuits directly to control an amplidyne. In this way, the amplidyne itself may act as an amplifier,* in turn driving loads that require many horsepower.

In many industrial circuits, the amplidyne is used as an exciter, supplying field current to a larger generator, as shown in Fig. 28*D*.

28-3. Amplidyne Fields.—In its simplest form, the amplidyne generator is controlled by just one field winding *F*† as in Fig. 28*C*. However, such a field winding is so small that three or four like it can be placed within the available space; in this way we can control one amplidyne generator from several signals at the same time. Figure 28*D* shows such an amplidyne generator being controlled by three separate fields *H*, *S* and *V*; its armature *A* supplies direct current to the field of a larger generator *G*. We can control hundreds of kilowatts' output at *O* merely by changing the 1-watt signal at *H*, *S* or *V*.‡

Field *V* lets the amplidyne of Fig. 28*D* act as a regulator to hold constant generator voltage at *GV*. Here you first select the desired generator voltage by turning *R*; the voltage *RV* comes from some standard supply, such as a battery or a voltage-regulator tube. Notice that, if this reference voltage *RV* is just equal to the generator voltage *GV*, there is no voltage drop across amplidyne field *V*, and no current flowing in this field winding;

* The amplidyne gives great amplification and is the logical connecting link between electronic control circuits and large d-c apparatus. In a similar way, the saturable reactor[28-6] is used as a connecting link between electronic control circuits and large a-c apparatus.

† There is also the compensating field *P*. The compensating and main control-field windings of an amplidyne have the same magnetic axis as the load current in the armature.

‡ Figure 28*D* does not show circuit refinements that improve stability.

alone, V now causes no output from amplidyne A, so there can be little voltage at GV. In operation, GV finally becomes several volts less than RV; this voltage difference forces just enough current through field V so that the amplidyne A excites the generator G to produce voltage GV. If some change of load causes GV to decrease, the voltage difference between GV and RV increases, quickly strengthening field V; this strengthens the field of G, to bring GV back to normal.

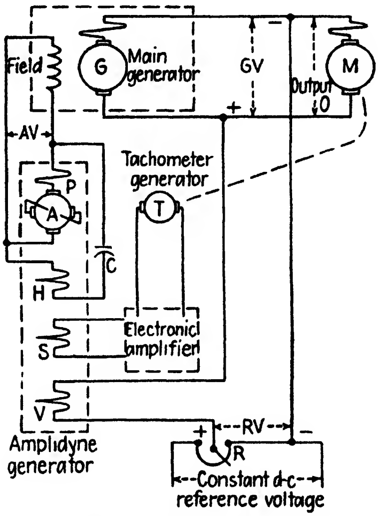


FIG. 28D.—Separate amplidyne fields regulate voltage, control speed, and decrease hunting.

To hold constant speed (in Fig. 28D) of a motor M that operates as the main load on generator G, we see that amplidyne field S controls A and the field of G to produce such speed control. If the speed of M drops, the voltage of T decreases; this tiny voltage change at T is amplified to produce enough change of current in field S, to boost GV and raise the speed of motor M to normal.

28-4. Antihunt Methods.—In most regulating systems, such as that shown in Fig. 28D, we need an antihunt, or stabilizing circuit;[17-10] without it the generator voltage GV may rise and fall (or "hunt") so rapidly that the system cannot settle down to a steady voltage. Field H is an antihunt field; because of its connection in series with capacitor C, it can act only when circuit voltages are changing. When the amplidyne output voltage AV is steady or constant, capacitor C has charged to this voltage AV; no current flows now into or out of C, so there is no current in field H. If AV increases slowly, capacitor C will charge to this higher voltage by drawing so little current through H that its effect may be neglected; when AV increases quickly, the large current needed to charge C also causes such a signal in field H that it "bucks down" the amplidyne output AV. By the stopping of such changes in amplidyne voltage, the rest of the system is likewise prevented from hunting.

Sometimes the antihunt signal is produced by using a transformer instead of capacitor C just described. In Fig. 28E such an antihunt transformer is shown,* with its primary winding connected across the amplidyne output voltage AV. Is it strange to see an a-c transformer used in a d-c circuit? The d-c voltage AV forces current through AHT primary (1-to-2); no voltage is produced at AHT secondary (3-to-4) as long as AV remains steady. Remember that a transformer's secondary, or output, voltage is produced by a *change* in primary, or input, voltage. If AV suddenly increases, AHT quickly produces a secondary voltage, which forces current through field H in such direction as to "buck down," or reduce, AV.

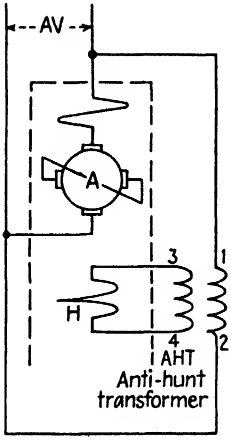


FIG. 28E. Antihunt transformer used with an amplidyne.

28-5. The Peaking Transformer.—This transformer produces peaks of voltage from its secondary winding, as shown in Fig. 28F, although its primary input voltage is a sine wave. It is an ordinary two-winding transformer, except that its special iron core contains much less metal than most transformers of the same size. The type more often used in resistance-welding heat-control circuits[13-9] is called a *resistance peaker*, for a large resistance is used in series with its primary winding to make the voltage peaks occur at the desired position.

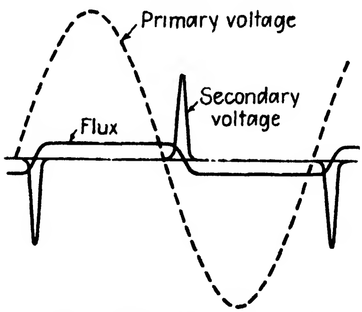


FIG. 28F.—Waveshapes of a resistance peaking transformer.

When an ordinary transformer (with plenty of iron in its core) operates with such a primary resistor, the resulting curves are shown in Fig. 28G. Notice that the primary current, which also magnetizes the iron, is nearly in phase with the primary voltage; the resulting flux is also a sine wave. When this flux is at its highest point A, the amount of flux is not changing at that instant, so no secondary voltage is

* See also Sec. 17-12.

produced, as at *B*. However ¼ cycle later, when flux is zero (at *C*) the amount of flux is changing so rapidly that it produces the greatest secondary voltage *D*.

In Fig. 28*H*, curves 1 and 2 again show how the flux changes smoothly in an ordinary transformer, producing a smooth sine wave of secondary voltage. However, if the amount of transformer iron is purposely decreased in the section around which the secondary is wound, then this smaller amount of iron cannot hold the usual amount of magnetic flux. When the primary current increases, the flux increases in this iron up to the limit where the flux cannot increase further. The iron becomes "saturated," so the amount of flux must stop changing, as in the flat part of curve 3 of Fig. 28*H*. The flux is changing normally between *A* and *B*. However, there is not enough iron to let the flux increase

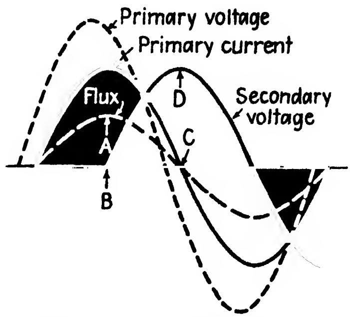


FIG. 28*G*.—Waveshapes of a standard transformer (with series resistance).

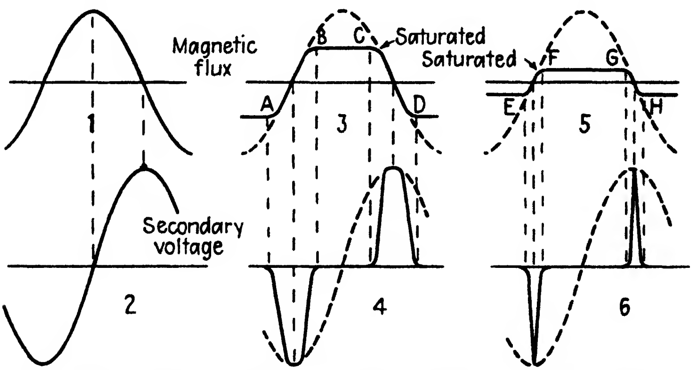


FIG. 28*H*.—Producing the peaked wave of the peaking transformer.

higher than *B*, so the flux does not change further until it is time to decrease at *C*. The flux changes normally between *C* and *D*, but cannot change beyond *D*. As curve 2 shows the secondary voltage produced by the gradual flux changes of curve 1, so curve 4 shows the secondary voltage produced by the flattened flux

curve of 3. Between *C* and *D*, where the flux is changing normally, the secondary voltage is as high as usual. Between *B* and *C*, where the flux is not changing, there can be no secondary voltage.

To make a peaking transformer with a steep, narrow peak, the core material (like transformer iron) is carefully designed so that it becomes saturated very soon after the magnetizing current changes direction, as shown in curve 5 of Fig. 28*H*. The magnetic flux remains constant so long (*F* to *G*) that only a very small part of each cycle remains (*E* to *F*, and *G* to *H*) for producing the secondary voltage peaks of curve 6. In this way, a saturated transformer produces a voltage peak at the instant when its flux is crossing the center line.

If we fit these voltage peaks into their proper places in Fig. 28*G*, the curves of Fig. 28*F* result. This resistance peaker produces its secondary voltage peaks near the beginning of each cycle of primary voltage.*

28-6. The Saturable Reactor.†—This is a variable inductance; it looks like a transformer and has two separate windings on an iron core, as sketched in Fig. 28*I*.‡ When no current flows in the direct-current winding, the reactor has large inductance; it acts as a "choke," preventing the flow of much alternating current through its a-c winding. However, when even a few milliamperes of direct current flow through the many turns of this d-c winding, the iron core becomes saturated and it loses its inductive effect; it is less able to prevent a.c. from flowing through its a-c winding (just as withdrawing the plunger of a solenoid decreases the effect of the plunger iron, so that the solenoid's inductance decreases). Briefly, we increase the flow of alternat-

* A capacitor and a reactor are sometimes connected in series with the primary of a peaking transformer, to act as a resonance filter; their sizes are selected so as to permit 60-cycle current to get through to energize the peaker, yet they prevent voltage transients from causing unwanted peaks.

† This is more properly called a saturable-core reactor.[14-1] COCKRELL, W. D.: "Industrial Electronic Control," p. 84, McGraw-Hill Book Company, Inc., New York, 1944.

‡ Figure 28*I* shows an iron core with four legs. Half of the a-c winding is wound on each of two inside legs; these half windings are connected so that no voltage is induced in the d-c winding. Many saturable reactors are built with a three-legged core; here the d-c winding surrounds the center leg, while half the a-c winding is on each outside leg. These a-c half windings are connected either in series or in parallel.

ing current through this saturable reactor when we increase the amount of current in its d-c winding

The symbol of the saturable reactor appears also in Fig. 28*I*. In elementary diagrams,[8-2] the d-c winding is sometimes shown separately from the a-c winding. (see Fig. 16*C*).

When a saturable reactor is used in control circuits, such as for phase shifting,[16-4] it may be smaller than a fist. When it is used directly to increase or decrease the a-c voltage applied to furnace loads,[14-8] motors or banks of lamps, such a reactor is rated from 1 to several hundred kva and may weigh hundreds of pounds.

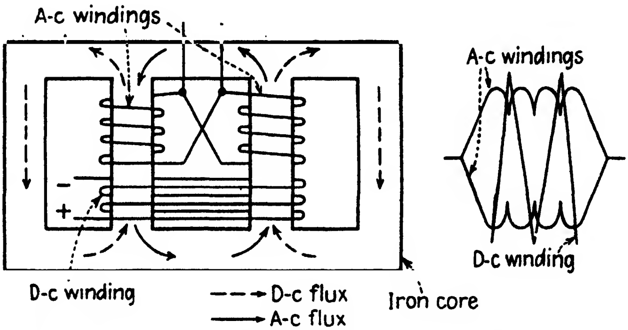


FIG. 28*I*.—Arrangement of windings in a saturable reactor.

Notice that the saturable reactor acts as an amplifier; a few watts of d-c input may control many kva of a-c load. Since it is controlled by an amount of direct current that may pass through an electron tube, it is a logical connecting link between electronic control circuits and large a-c loads.*

The action of such a reactor is shown in Fig. 28*J*. The a-c winding of saturable reactor *SX* is connected in series with resistor *R*, across a steady a-c voltage *Z*. When no direct current flows in the d-c winding of *SX*, the a-c voltage *X* (across *SX*) is much greater than the a-c voltage *Y* (across *R*); this is the condition shown in part (*a*).

At the left in Fig. 28*J*, curve 1-2-3-4 shows how the magnetism, or flux, in *SX* increases (upward) as the current in either *SX* winding increases (toward the right). With no d.c. flowing in

* The Nicaloi-core reactor (described in Sec. 18-9) differs from that above, for it is self-saturating; it has only one winding.

SX, the only magnetic flux is caused by a small current in the a-c winding; when this magnetizing current is zero (at 1) there is no flux. Once each cycle, the current increases to point 5; this

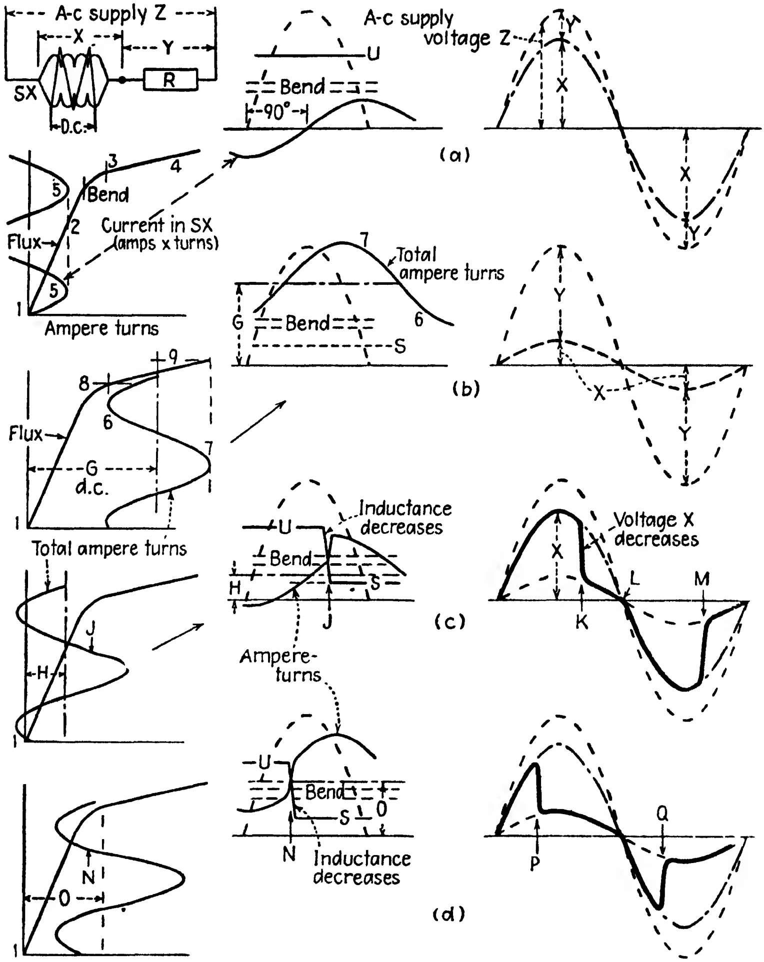


FIG. 28J.—Waveshapes in a saturable-reactor circuit as the amount of d.c. changes.

increases the flux to 2. This large change of flux (from 1 to 2) each cycle causes the "choke" effect, which limits the amount of alternating current in SX; here SX has large inductance, shown by the line U.

Part (*b*) of Fig. 28*J* shows that direct current (flowing in the d-c winding of *SX*) may make the reactor operate between points 3 and 4 on the curve. Here the largest amount of direct current is flowing; it may be only 1 or 2 milliamperes, but it flows through so many turns of wire (wound around the iron core of *SX*) that it has the large effect shown at *G*. There is also the effect of the current in the a-c winding, so that the effect of these combined currents changes between 6 and 7. Notice that this 6-to-7 change causes only a small increase of magnetic flux, upward from 8 to 9. This flux cannot change more, for here the iron is nearly saturated; the bend in the curve (between 2 and 3) shows that the iron is nearly all magnetized. Since the flux does not change much, *SX* now has little "choke" effect; much more alternating current may flow through the a-c winding. The a-c voltage *X* across the reactor is now small; the greater current causes large voltage *Y* across the resistor. Here the reactor *SX* has small inductance, shown by the line *S*.*

28-7. Reactor Curves—Medium Saturation.—This far, Fig. 28*J* shows that the voltage *X* across the reactor is a sine wave, when *SX* either has no current in its d-c winding or has so much direct current that *SX* operates far above the bend of the curve. When the direct current is decreased to a medium flow, *SX* has a medium amount of inductance; however, the curve of voltage *X* across the reactor is no longer a sine wave, as shown by the heavy lines in parts (*c*) and (*d*).

In part (*c*), the direct current in *SX* is small, and its effect is shown at *H*. The reactor operates on the steep part of the curve 1-2, except during a small part of each a-c wave of magnetizing current. At *J* this current rises high enough to increase the flux to a value above the bend. At this instant, the iron of the reactor *SX* becomes saturated;† the inductance of *SX* changes suddenly from a large to a small amount. At the same instant (at *K*) the reactor voltage *X* decreases. As the a-c supply volt-

* The a-c wave above line *S* is more nearly in phase with the a-c supply voltage, since *SX* has lost most of its inductive effect, and the current is limited mainly by resistance *R*.

† The magnetism increases more slowly at first, but this permits greater current flow in the a-c winding, saturating the iron further; quickly the iron of *SX* changes from an unsaturated to a saturated condition, once during each half cycle.

age reverses (at L) at the start of the next half cycle, SX becomes saturated again at point M.

If the direct current in SX is now increased slightly, part (d) of Fig. 28J shows that SX operates above the bend during a larger part of the cycle. Earlier in the half cycle, at N, the iron of SX becomes saturated suddenly, and the reactor voltage X decreases sharply at P, and again at Q. These abrupt voltage

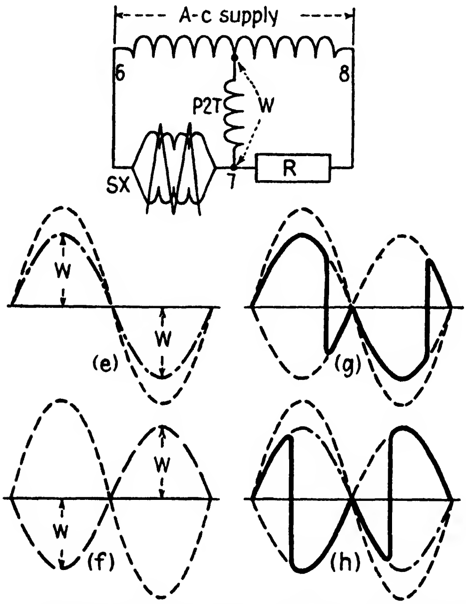


FIG. 28K.—Waveshapes in a saturable-reactor phase-shifting bridge.

changes (as at K, M, P or Q) serve well to control tube-grid circuits. Notice that a gradual increase of direct current in SX decreases the *average* inductance during the cycle; at any instant, SX has either large inductance or very little inductance.

28-8. Voltage Curves in a Phase-shifting Bridge.—When a saturable reactor is used in the circuit of Fig. 28K (and as described in Sec. 24-3), a queer waveshape of voltage appears at W, applied to transformer $P2T$. Part (e) shows that, with no d.c. flowing in SX, the voltage W is a sine wave nearly in phase with the a-c supply voltage (as though points 7 and 8 were together). With large d.c. saturating SX, part (f) shows that the sine wave of voltage W is now about 180 degrees out of phase

with the a-c supply (as though points 7 and 6 were together). With medium amounts of direct current in SX, parts (g) and (h) show how voltage W switches suddenly from the in-phase curve to the out-of-phase curve; the solid lines show how the voltage waveshape changes as the amount of d.c. increases, causing the abrupt voltage change to occur earlier in each half cycle. By proper connection of the secondary leads of transformer $2T$, each sudden saturation of SX is made to cause a sharp voltage rise, which may serve to fire a thyratron tube.

28-9. Constant-voltage Transformer, or Stabilizer.—There are many types of this voltage-regulating transformer. Generally such a unit includes a capacitor, together with several reactors, or windings on a special magnetic core. By cleverly combining the voltages* across these various parts, this combination furnishes more constant output voltage. If its input or voltage supply changes, the transformer absorbs this voltage change, keeping its output rms voltage unchanged. To accomplish this, the waveshape of its output may change, but this is often unimportant, as when its output is to be rectified and filtered for a d-c supply to an electronic circuit. Since there are no moving parts, the output voltage is corrected within two or three cycles after the input voltage, or the load, changes.

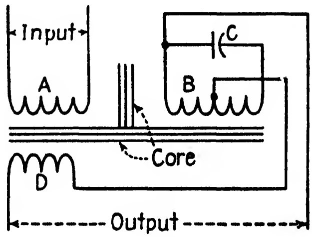


FIG. 28L.—Circuit of a constant-voltage transformer (resonant type).

In one type shown in Fig. 28L, the input winding A is on one portion of the iron core and directly induces voltage only in winding D. On another portion of the core is the B winding, or coil, which is connected across capacitor C (also mounted inside the transformer case). The size of capacitor C is chosen just large enough so that $1/2\pi fC = 2\pi fL$.† This combination of winding B and capacitor C is resonant at 60 cycles. A large current flows backward and forward through B and C, exactly in step with the 60-cycle pulse of energy received through the iron core from winding A. Notice that the amount of this oscillating

* To see how these voltages combine, a vector diagram is used, as shown in J. A. Uttal's Voltage Stabilizers, *Electronic Industries*, August, 1945.

† Here f equals 60 for a 60-cycle transformer; C is in farads, L is in henries.

current depends mainly on the constants (henries or farads) of *B* and *C*, and does not increase when the voltage across *A* increases. This is like a grandfather's clock, where the amount of swing of the pendulum remains the same whether the clock spring is wound tight or loose; the spring supplies only the pulses of energy needed to keep the pendulum swinging. Since this current swings between constant limits (and since the core inside *B* becomes saturated), the voltage across coil *B* remains fairly constant; part of it is used to furnish most of the output voltage of the transformer. Coil *D* furnishes a small part of the output

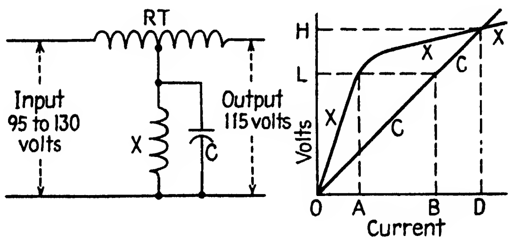


FIG. 28*M*. Constant-voltage transformer using self-saturating reactor.

voltage and further corrects or keeps the output voltage at a steady value.

Another type of voltage stabilizer is shown in Fig. 28*M*, and includes transformer *RT*, capacitor *C* and reactor *X*. *X* is designed so that its iron core saturates to give the performance curve *X*. When the input voltage is low, at *L*, notice that the current *A* passing through reactor *X* is much less than the current *B* passing into capacitor *C*. However, at high voltage *H*, the amount of current *D* through reactor *X* is about equal to the current into capacitor *C*. When the input voltage is high, the current *D* passing into *C* (offset by equal current *D* passing through *X*) causes a voltage drop through the primary winding of *RT*, so that the output voltage is less. However, when the input voltage is low, the current *B* into the capacitor *C* (unmatched by current *A*) causes a voltage rise across the primary of *RT*, so that the output voltage is greater than the input.

28-10. The Selsyn—Electric Gearing.—The selsyn* is a kind of motor, or generator. When two selsyns are connected

* SHOULTS, D. R., C. J. RIFE, and T. C. JOHNSON, "Electric Motors in Industry," p. 168, John Wiley & Sons, Inc., New York, 1942. See also

together electrically, any movement of the shaft of selsyn 1 causes the shaft of selsyn 2 to turn the same amount, as though the two selsyn shafts were mechanically geared together. If pointers are mounted properly on each of the selsyn shafts, and selsyn 1 is pointed at a certain mark on a dial, selsyn 2 will point to the corresponding mark on a duplicate dial. For such indicating purposes, the selsyns are small units that operate from single-phase a-c power supply, as is shown in Fig. 28*N*. Similar units, designed to operate on direct current, will also indicate position.*

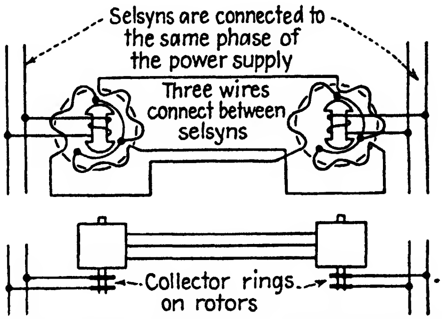


FIG. 28*N*.—Connections of single-phase indicator selsyns.

Larger units, called *power selsyns*, operate from a three-phase power supply, as shown in Fig. 28*O*. Such power selsyns act like wound-rotor ("slip-ring") induction motors, where the three collector rings of one motor are connected to the three rings of the other duplicate motor. When a-c power is connected to the stators of both selsyns, their rotors "lock together" in one position. Neither rotor tries to turn further, for there is no secondary current; the secondary, or collector-ring, voltage of one selsyn is exactly balanced or opposed by the secondary voltage of the other selsyn. However, when you turn the shaft of selsyn 1, you change the phase position of its rotor and upset this balance; current flows through the collector-ring circuit, making selsyn 2 turn at the same speed as selsyn 1. In this way, if you drive selsyn 1 at, say, 1000 rpm (by some other motor), selsyn 1

CHILDS, R. S., Magnesyn Remote Indication, *Electrical Engineering*, September, 1944; and JOHNSON, T. C., Selsyn Design and Application, *Electrical Engineering*, October, 1945.

* JEWELL, R. G., and H. T. FAUS. A D-c Selsyn for Aircraft, *Electrical Engineering*, June, 1942.

acts as a generator and drives selsyn 2 at exactly 1,000 rpm also. Here selsyn 1 is a transmitter, selsyn 2 is a receiver. Several receivers may be operated from one larger transmitter.

If a 10-hp selsyn is on the same shaft with a 10-hp motor, driving a load, while a duplicate selsyn and motor are driving another load, then neither selsyn does any of the work as long as both motors turn at exactly the same speed. If for any reason motor 2 tries to turn more slowly than motor 1, selsyn 2 begins to lag behind selsyn 1; owing to this lag, selsyn 2 immediately acts as a motor, drawing power from the three-phase supply. This decreases the load on motor 2 but increases the load on motor

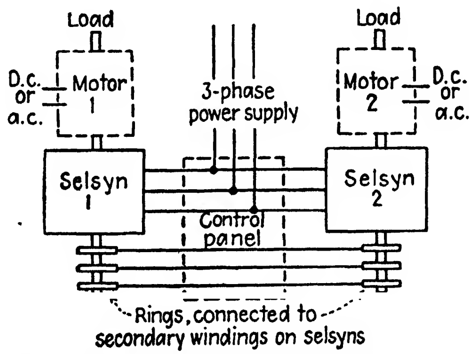


FIG. 28O.—Three-phase power selsyns lock together two motor shafts.

1, so that they turn at the same speed. Perhaps one selsyn lags as much as 20 degrees behind the other selsyn; when the load (transmitted electrically from one selsyn to the other) decreases, there is less lag or angular difference between them.

Instead of using large power selsyns to transmit the kilowatts needed to keep two shafts in step, or synchronized, small selsyns sometimes control electronic amplifiers and amplidynes,[28-2] which control the shaft-driving motors. The current input to either selsyn stator is lowest when the two selsyns are in step; when one selsyn lags 1 or 2 degrees, the rise in input current signals the electronic circuit so that one of the amplidynes corrects the shaft speed.

28-11. The Differential Selsyn or Phase Shifter.—In the electric circuit between any pair of selsyns already described, a third, or differential, selsyn may be inserted, shown as *D* in Fig. 28*P*; the movement of *D* is equal to the difference between

the movement of A and the movement of B.* If selsyns A and B are turning at exactly the same speed, D does not move; if A turns 1000 rpm forward and B turns 999 rpm forward, D turns 1 rpm backward.

If an arrow is mounted on each of the three selsyn shafts and pointed at 2 (in lower portion of Fig. 28P), these things will happen: (1) if D is locked so it cannot turn, A and B will control each other as though D were not in the circuit; (2) if you hold A still at 2, and turn D from 2 to 3, B also moves from 2 to 3; (3) if you hold B still at 2, and turn D from 2 to 3, A moves from 2 to 1; (4) with A at 2, if you turn D to 5 and lock it there, B points

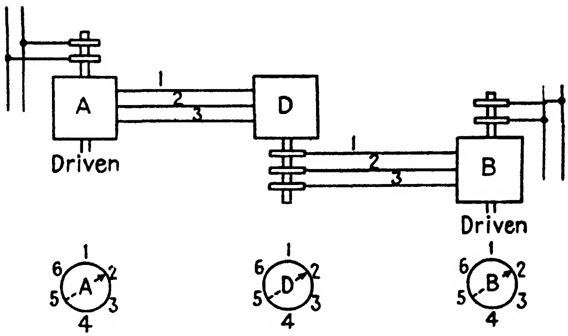


FIG. 28P.—Differential selsyn D may act as differential gear.

to 5, just opposite to A; if you now rotate A, B turns at the same speed as A, but is always opposite to A, or 180 degrees from A. Although D is not turning, the position of D controls the displacement between A and B; although A and B may both be turning at 1000 rpm, D is the phase shifter by which you can make the arrows of A and B both point at 2 at the same instant, or you can displace arrow B so that it lags behind A.

In electronic control circuits, a multiphase selsyn may be used as a phase shifter to produce output a-c voltages that are out of phase with the input, or supply, voltage. At one position of its shaft (shown at (a) in Fig. 28Q), the output voltage at its rings is in phase with the input voltage to its stator. If the shaft is moved one-sixth of a full turn, or 60 degrees, (b) of Fig. 28Q shows that the output voltage now lags 60 degrees behind the input voltage

* The differential selsyn D has three rings (like a three-phase unit), while selsyns A and B may be single-phase or three-phase units.

(or the output has been shifted 60 degrees out of phase). Turning the shaft to other positions produces other amounts of phase-shift of the output voltage.

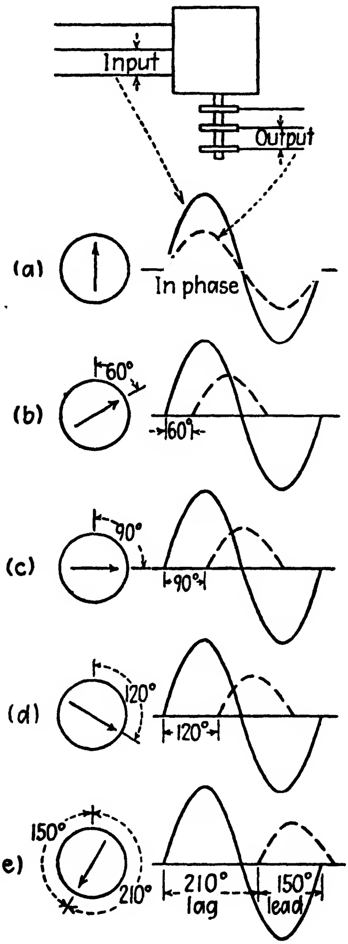


FIG. 28Q.—Using a selsyn phase shifter.

28-12. Thyrite.—Thyrite* is a resistance material made of silicon carbide and baked at high temperature. To give good electrical contact, its two flat surfaces are metal-sprayed. Smaller sizes may have wire leads.

Thyrite has a special action when you increase the voltage across it. When you double the voltage across an ordinary resistor, the current doubles also, since the amount of resistance stays unchanged. However, if you double the voltage across Thyrite, the current increases at least 11 times; this shows that the amount of resistance decreases greatly when the voltage increases. Thyrite may be used for lightning arresters; it passes very little current at ordinary line voltages; but when a lightning surge adds a high voltage, the resistance of the arrester material instantly decreases, letting the lightning pass through the arrester, protecting other equipment. When the high voltage has passed, the Thyrite resistance returns to normal. Similarly, Thyrite resistors are connected across transformers, motor fields or other inductive windings, to absorb or by-pass any voltage surge or "kick" when such circuits are opened.

* Trade name used by General Electric Company. See BROWNLEE, T., Calculation of Circuits Containing Thyrite, *General Electric Review*, April and May, 1934.

28-13. Metallic or Disk Rectifiers.—Many electronic equipments include rectifiers that are not electron tubes, but are assemblies of metal disks or plates. These are called *copper-oxide units;* more recently *selenium* rectifiers are being used.*

Each disk includes two or more different metallic layers, as is shown in Fig. 28*R*. Where these layers join, there is a blocking action that permits a large flow of electrons in one direction (from copper to copper oxide, or from counterelectrode to selenium), but offers much higher resistance to electron flow in the reverse direction. In the forward direction each disk alone may pass about 1 ampere or less, requiring about 1 volt between the two faces of the disk. However, when the voltage is reversed, 5 to 10 volts forces only a few milliamperes to flow; since this small reverse current may flow, the metallic rectifier does not have such complete or perfect rectifying ability as the electron tube.

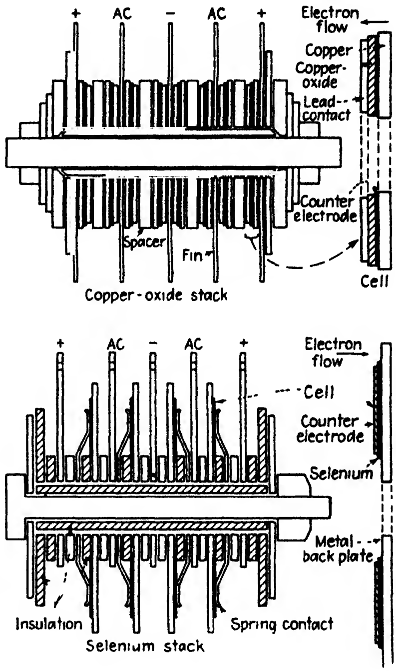


FIG. 28*R*.—Arrangement of disks in metallic rectifiers (full-wave bridge).

There are several sizes of rectifier disk; disks of one size are assembled in stacks, to provide the needed output current and voltage—more disks in series for greater voltage, more disks or stacks connected in parallel for greater current. For a simple single-phase half-wave rectifier, all disks are stacked in the same direction. For a rectifier with midtapped transformer (to pass both halves of the a-c wave, like the tube circuit in Fig. 2*I*),

* HAMANN, C. E., and E. A. HARTY, Fundamental Characteristics and Applications of the Copper-Oxide Rectifier, *General Electric Review*, August, 1933; HARTY, E. A., Characteristics and Application of Selenium-Rectifier Cells, *Electrical Engineering*, October, 1943; RAMSEY, G., The Selenium Rectifier, *Electrical Engineering*, December, 1944.

half the disks face in one direction, half face in the opposite. The most common metallic rectifier circuit is the full-wave bridge connection shown in Fig. 10*J* and Fig. 28*R*; here no transformer center tap is needed.

28-14. The Thermocouple.—This device lets us measure the temperature of very hot objects; it gives an electric signal whose strength increases as the temperaure rises. The thermocouple is made by joining together one end of pieces of two different metals, leaving the opposite ends of these two pieces separated. When the joined ends are heated to a much higher temperature than the loose ends, a small d-c voltage appears between the loose ends. The amount of such voltage is given in thousandths of a volt, or millivolts; this explains why delicate instruments or electronic circuits are needed to put this tiny signal to work.

28-15. The Ballast Tube.—This tube tries to hold constant current in the circuit in which it operates. Its current flows in a filament, like the current in an incandescent lamp, therefore this ballast tube* is not electronic. Its filament (usually made of iron) is heated by the load current passing through it. Within its operating range, any increase of load current raises the temperature of part of the filament and increases the resistance of the filament. After a short time lag, this resistance has increased the right amount to bring the current back to its previous value.

28-16. The Vacuum Contact Tube or Switch.—This tube is not electronic; it is merely a set of metal contact points enclosed in a glass or metal tube so that the points may operate in high vacuum. In this way these tips may close or open an electric circuit by less tip movement than is needed in air.

28-17. Mercury-contact Tubes.—Built in many forms and shapes, these tubes contain liquid mercury. When the tube is held in one position, the mercury forms a metallic circuit between contacts built through the tube wall; when the tube is tilted, the mercury flows to another part of the tube, opening one electric circuit, or perhaps closing a different circuit. Such tubes, or switches, are not electronic.

* COCKRELL, W. D., "Industrial Electronic Control," p. 5, McGraw-Hill Book Company, Inc., New York, 1944.

CORRELATED LIST OF VISUAL AIDS

The following list of visual aids can be used to supplement some of the material in this book. These films and filmstrips can be secured from the producer or distributor listed with each title. In many cases these films and filmstrips can also be secured from your local film library or local film distributor. (The addresses of these producers or distributors are listed at the end of the bibliography.)

The running time (min), whether it is silent (si) or sound (sd), motion picture (MP), filmstrip (FS), or color (C) is listed with each title. All those not listed as in color are black and white. All of the motion pictures are 16 mm; filmstrips are 35 mm.

Each film has been listed only once, usually in the first chapter to which it is applicable. However, in many cases it can be used advantageously in several of the other chapters.

Each of the motion pictures produced by the U. S. Office of Education has a coordinated silent filmstrip and an instructor's manual. Often other films and filmstrips have accompanying instructor's manuals.

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Electronics—An Introduction (USOE 16 min sd MP). Explains the nature of electrons and electronic flow.

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Electrons on Parade (Ganz 20 min sd MP). Shows the construction of a power tube and explains the different uses of the tube.

Modern Aladdin's Lamp (WE 20 min sd MP). Traces the development of the vacuum tube and shows in detail how it is made and its many applications in everyday life.

Alternating Current (Castle si FS). Elementary introduction to the principles of alternating current.

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EBF—Encyclopaedia Britannica Films, Inc., 1801 Broadway, New York 19, N. Y.

Ganz, William J. Company, 40 East 49th St., New York, N. Y.

GE—General Electric Company, Visual Instruction Section, 1 River Road, Schenectady, New York.

Lincoln Electric Company, 12818 Coit St., Cleveland 1, Ohio.

Linde Air Products, 205 East 42nd St., New York, N. Y.

USOE—U. S. Office of Education (Obtainable from Castle Films, Inc.)

WE—Western Electric Company, Inc., 195 Broadway, New York, N. Y.

Westinghouse Electric Corporation, 246 East 4th St., Mansfield, Ohio.

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E

ANSWERS

apter 3

T
F
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F
F
T

Chapter 4

1. F
2. F
3. T
4. F
5. T

Chapter 5

1. T
2. F
3. F
4. T
5. F
6. *b*

Chapter 6

1. 2*R*
2. *a*
3. F
4. F
5. T
6. F
7. F

apter 7

40 ma
No change
c
6, 3
F, T
F
F, T, F
F
F
F, F, T
F
2. F
3. T
4. F

Chapter 8

1. *b*, *c*, *e*; 8*C*
2. *a*, *c*
3*a* No
3*b* No
3*c* Large tube-*C* current
3*d* Nothing; no 4*R* voltage
4. With much light on *P*; 3*R* turned clockwise

Chapter 9

1. 15v, 0, 0, 300 volts, 285 volts
2. Full, full, full, 0, full
3. *c*, *d*
4. T
5. T
6. F
7. F
8. F
9. T
10. T

apter 10

1. None
2. Overload
3*a* Becomes ½
3*b* Becomes 0
3*c* No change
4. 10*K*, largest; 9*B*, smallest
F
6. T, F
7. F

Chapter 11

1. *b*, *d*, *f*
2. F
3. T
4. F
5. F
6. F
7. T
8. T
9. F
10. T
11. T
12. F
13. T
14. F
15. T
16. F

Chapter 12

1. F
2. F
3. T
4. F
5. T
6. F
7. T
8. F
9. F
10. T, F
11. About 4 cycles
12. Welding current will not stop
13. About 1 mu f
14. 0.001
15. Removes synchronous starting, so heat varies

Chapter 13

1. T
2. F
3. T
4. F
5. F
6. F
7. T
8. F
9. T
10. T
11. T
12. F
13. F
14. *c*, *e*, *f*, *h*
15. *a*, *d*, *g*

Chapter 14

1. F
2. T
3. T
4. F
5. T (+up)
6. T
7. T
8. F
9. T
10. F
11. T

Chapter 15

1. 85 volts, 0
2. $2\frac{1}{2}$
3. Tube 7, tube 8, 6*T*, tube 5
4. 21 to 19
5. T
6. F
7. T
8. T
9. T, F
10. T
11. F (*CRF* opens)
12. F
13. T

Chapter 16

1. F
2. F
3. F
4. T
5. F
6. *c*
7. *a*
8. *b*
9. *a*

Chapter 17

1. T
2. T
3. F
4. T
5. T
6. F
7. F
8. T
9. T
10. *d*

Chapter 18

1. *b*, *c*, *e*, *h*
2. T
3. F
4. F
5. T
6. T
7. F
8. F

Chapter 19

1. *c*, *d*, *e*, *i*
2. F
3. F
4. T
5. T
6. F
7. F
8. T
9. F
10. T
11. F
12. F
13. F

Chapter 20

1. F
2. T
3. F
4. T
5. F
6. F
7. T
8. T
9. T
10. T
11. F
12. T
13. T
14. F

Chapter 21

1. T
2. F
3. T
4. T
5. F
6. T
7. F
8. F
9. T
10. T
11. F

Chapter 22

1. F
2. T
3. F
4. F
5. T
6. F
7. T
8. F
9. F
10. F
11. T
12. T

Chapter 23

1. T
2. T
3. F
4. T
5. F
6. T
7. T
8. T
9. F

Chapter 24

1. *C*, *CC*, *E*, *EE*, *F*, *H* and either 1 or 2
2. T
3. F
4. F
5. T
6. F
7. F
8. T
9. T
10. F
11. F

Chapter 25

1. *c*
2. T
3. T
4. F
5. F
6. F
7. F
8. T
9. F
10. F
11. F

Chapter 26

1. F
. T
.. F
:. T
. T
. T, T
. F
. F, T
· T
F

Chapter 27

1. $5R$
2. $1R$, $1C$; $7C$, $16R$; $6C$, $15R$; $10C$, $4R$; $1C$, tube 3
3. T
4. F
5. F
6. T
7. F
8. F
9. T